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Volumetric Changes in the Kidney in Heart Failure Evaluated with Fully Automated Three-Dimensional CT Measurement: Association with Renal Function and Longitudinal Cardiac-Width Changes

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Abstract

Objectives: This study aimed to investigate renal volumetric changes in heart failure using fully automated three-dimensional (3D) CT volumetry and to examine their association with renal function and the progression of renal impairment. **Methods:** This retrospective study included 131 heart failure patients and 147 non-heart failure controls who underwent chest-abdominal CT. Fully automated 3D kidney segmentation was performed using deep learning-based image analysis software. Kidney volumes were measured and compared between groups. Patients with heart failure were further stratified by renal function (estimated glomerular filtration rate [eGFR] ≥ 30 vs. <30 mL/min/1.73 m^2), and longitudinal changes were evaluated in those who underwent follow-up CT. **Results:** Heart failure patients had significantly lower total kidney volumes (median [interquartile range]: 224 [96] mL) compared to the control group (263 [84] mL, $p < 0.0001$). Among patients with eGFR < 30, the left kidney was numerically smaller than the right (86 [35] vs. 92 [28] mL), but not significantly so ($p = 0.0564$). Longitudinal follow-up demonstrated significant increases in kidney volume in increased cardiac width cases ($n = 20$), although congestion was not directly assessed, and kidney volume reduction in patients with a decreased cardiac width ($n = 34$), without establishing decongestion or renal atrophy. **Conclusions:** Automated 3D CT volumetry provides an objective assessment of renal involvement in heart failure. Left–right volume differences were exploratory and did not establish predictive value. Prospective studies are needed to determine their clinical significance.

Keywords: computed tomography; volumetry; deep learning; kidney; heart failure

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Academic Editor: Marijn Speeckaert

Received: 30 October 2026
Revised: 20 November 2026
Accepted: 24 November 2026
Published: 26 November 2026

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1. Introduction

Heart failure is a complex clinical syndrome characterized by impaired cardiac function, which leads to inadequate organ perfusion and systemic congestion. Recent global estimates indicate that heart failure affects approximately 55.5 million people (1–3% of the population) [1]. One of the most affected organs in this context is the kidney, and the interplay between heart and kidney dysfunction is well-recognized in the framework of cardiorenal syndrome (CRS) [2,3], which contributes to chronic kidney disease (CKD) progression and adverse clinical outcomes [4,5]. For instance, it has been reported that acute kidney injury occurs in approximately 30% of patients with acute heart failure requiring

hospitalization [6]. Despite advancements in heart failure management, the mechanisms underlying renal changes remain incompletely understood, highlighting the need for improved diagnostic tools and biomarkers to assess renal involvement in heart failure.

There are two possible pathological effects of heart failure on the kidneys. First, the low cardiac output caused by heart failure reduces blood flow to the renal parenchyma, possibly leading to renal dysfunction. On the other hand, the increase in right atrial pressure associated with heart failure, especially right heart failure, leads to an increase in renal venous pressure, causing congestion in the renal parenchyma. Furthermore, elevated renal interstitial pressure causes compression of the capillaries and renal tubules, increasing the intraluminal pressure of the renal tubule, reducing the intraglomerular pressure gradient, thereby decreasing glomerular filtration rate (GFR) [5,7]. Although these hemodynamic changes are presumed to be accompanied by changes in renal volume, the relationship between heart failure and renal volume changes is not well known.

Emerging evidence has highlighted the utility of imaging techniques—particularly fully automated three-dimensional (3D) organ segmentation and volumetric measurements derived from abdominal computed tomography (CT) [8–11]—in evaluating renal morphology and function. However, there have been few reports that these techniques have shown promise in objectively providing detailed insights into renal volume changes associated with heart failure.

Therefore, the aim of this study was to investigate renal volumetric changes in heart failure based on fully automated 3D CT volumetry using a deep learning algorithm and to examine the association with renal function and the progression of renal impairment. Because participants were selected from patients undergoing clinically indicated CT, the study sample was not intended to estimate population prevalence of heart failure.

2. Materials and Methods

2.1. Study Population

This single-center study was approved by the institutional review board of our institution, which waived the requirement for written informed consent due to the retrospective nature of the study. A total of 2126 patients who underwent chest-abdominal CT, with or without contrast material injection, were identified by a search of the picture archiving and communication system in our institution between February 2022 and June 2024. Among these, the inclusion criteria required participants to be adults aged 18 years or older and to have heart failure based on the information clinicians entered into CT examination request forms or the clinical diagnosis of heart failure recorded in clinical charts. Heart failure was defined as a clinical syndrome consisting of symptoms and/or signs, or findings of abnormal cardiac structure and function by echocardiography according to a previous study and guidelines [12,13]. Patients were excluded if they had protrusive kidney cysts affecting renal volume estimation ($n = 20$), inaccurate kidney segmentation ($n = 14$), incomplete kidney coverage by abdominal CT ($n = 6$), severe hydronephrosis ($n = 1$), lack of laboratory data ($n = 1$), or a clinical history of kidney surgery ($n = 1$). Inaccurate kidney segmentation refers to cases where the automatically segmented area is visually confirmed to be inaccurate (probably due to the unclear boundary resulting from using unenhanced CT). Finally, 131 patients with heart failure (heart failure group) were included in this study (80 men, 51 women; mean age, 73.6 ± 13.7 [range, 28–93] years old) (Figure 1). The heart failure group was further stratified into subgroups based on eGFR ≥ 30 mL/min/1.73 m^2 or eGFR < 30 to assess the differences in renal volumes.

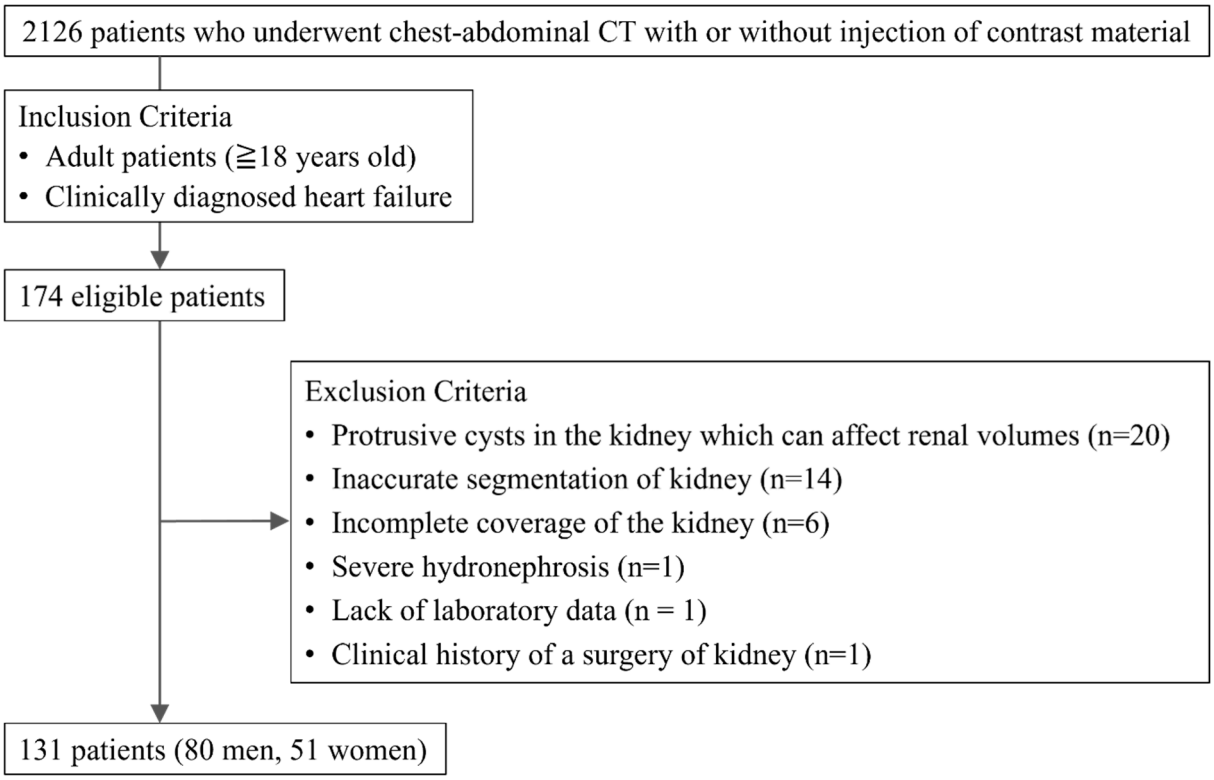

Figure 1. Patient flowchart.

In addition, 147 patients who had no clinical history of heart failure and who underwent both unenhanced and contrast-enhanced CT were included as a control group (non-heart failure group). The control group was selected from patients who met all inclusion criteria and did not meet any exclusion criteria, and who had undergone CT within two months of the end of the study period. The inclusion criterion for the control group was that heart failure was not registered in the patient's current medical history, and the same exclusion criteria as for the heart failure group were applied. Contrast-enhanced CT in this group was used for anatomical measurements of renal vasculature. The reasons for chest-abdominal CT included a further evaluation of suspected colorectal lesions ($n = 53$), pancreatic lesions ($n = 25$), gastroduodenal lesions (e.g., gastric cancers) ($n = 22$), hepatic lesions (e.g., hemangioma) ($n = 31$), gallbladder lesions ($n = 4$) or other lesions ($n = 12$). There were 85 men and 62 women with mean ages of 67 ± 14 (range, 19–92) years old. Patient demographics and clinical information were obtained from electronic health records. The control group (non-heart failure group) was further stratified into subgroups based on kidney volume asymmetry: the group in which the right kidney volume exceeded the left kidney volume (large right kidney group) and the group in which the right kidney volume was less than the left kidney volume (large left kidney group), and the kidney volumes were compared between two groups.

2.2. CT Technique

CT images were acquired using a multi-detector CT scanner from multiple vendors (SOMATOM Force and Drive, SIEMENS Healthineers, Erlangen, Germany; Aquilion Precision, Canon Medical Systems, Otawara, Japan; Optima 660 Pro, GE HealthCare, Waukesha, WI, USA) in our hospital. The following imaging parameters were used: tube voltage of 100 or 120 kVp with modulated tube current; matrix size of 512 × 512; and slice thickness and reconstruction interval of 1.0 mm. Unenhanced CT images were obtained in all patients in a cephalocaudal direction, and used for volume measurements of the kidney.

Contrast-enhanced CT images were obtained in the control group (non-heart failure group) using a body-weight-adapted dose (600 mg I/kg) of non-ionic contrast material at an injection time of 30 s (injection flow rate ranged from 3 to 5 mL/s, depending on the patient's weight), followed by a 30-mL saline flush. These images were used for anatomical measurements of renal vasculature.

2.3. Imaging Analyses

Fully automated segmentation and 3D volumetric CT measurements for the kidney were performed using a dedicated image viewing software equipped with an integrated organ segmentation tool (SYNAPSE SAI viewer, version 2.5; Fujifilm, Tokyo, Japan). The analysis was conducted by a single radiologist with two years of experience in abdominal imaging on a workstation. This process was carried out without access to clinical information and laboratory data. The software automatically identified and delineated the kidney boundaries on all 1-mm slices of unenhanced CT scans. It then computed the segmented areas, and calculated the total organ volumes on the unenhanced images. The segmented kidney areas were visually highlighted on the screen, and the corresponding volumetric measurements were automatically displayed for subsequent data analysis (Figure 2). Small renal cysts were included in the segmented volume, whereas the renal sinus was automatically excluded. Patients with protruding cysts affecting kidney volume were excluded because automated cyst removal was unavailable. No manual segmentation corrections were performed. The first CT scan during the study period was included in the initial analysis for patients in the heart failure group with follow-up CT examinations. In addition, maximum transverse cardiac width in the heart failure group was measured on axial CT images by the same radiologist. Patients with follow-up CT scans were classified into increased or decreased cardiac width groups according to the change in maximum transverse cardiac width [14]. This linear measure does not directly quantify cardiac volume or clinical heart failure severity. The selection criteria for follow-up CT were that the CT imaging was performed within the study period and that a chest-abdominal CT scan was performed. The volumetric longitudinal changes in the kidney as well as the differences between right and left kidney volume were analyzed. Additionally, in the decreased cardiac width group, the analysis comparing patients with a follow-up period of ≤2 months and those with >2 months was conducted.

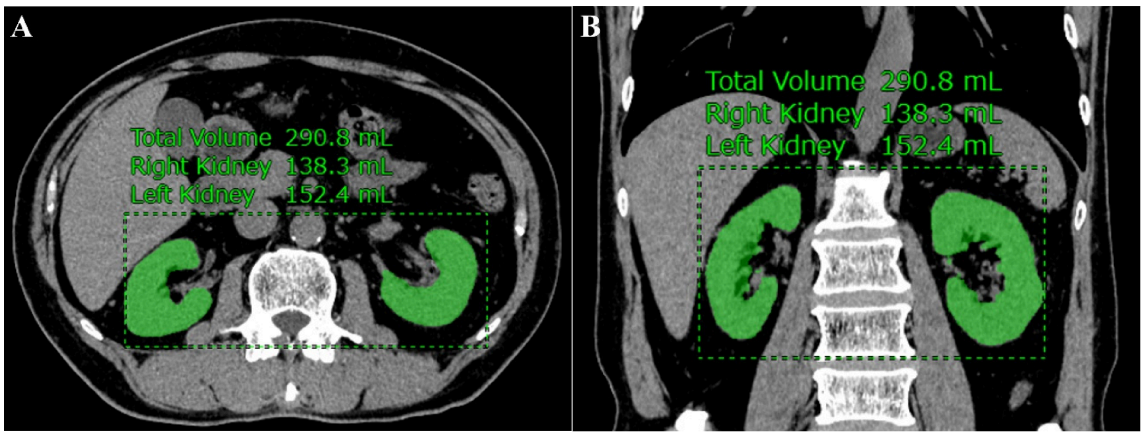

Figure 2. Fully automated 3D volumetric CT measurement of the abdominal organs using a deep learning algorithm. Axial (**A**) and coronal (**B**) CT images showing the automatically segmented area of the kidney in green.

In the control group (non-heart failure group), the distance between the aorta and the superior mesenteric artery (aorta/SMA distance) and the maximum diameter of the left

renal vein and inferior vena cava (IVC) were also measured as anatomical measurements of renal vasculature on contrast-enhanced axial CT images (Figure 3) in order to evaluate the relationship between laterality differences in renal volumes and variations in vascular anatomy and physiology. No accessory renal arteries, severe renal artery stenosis, or retroaortic left renal veins were identified in the contrast-enhanced control group.

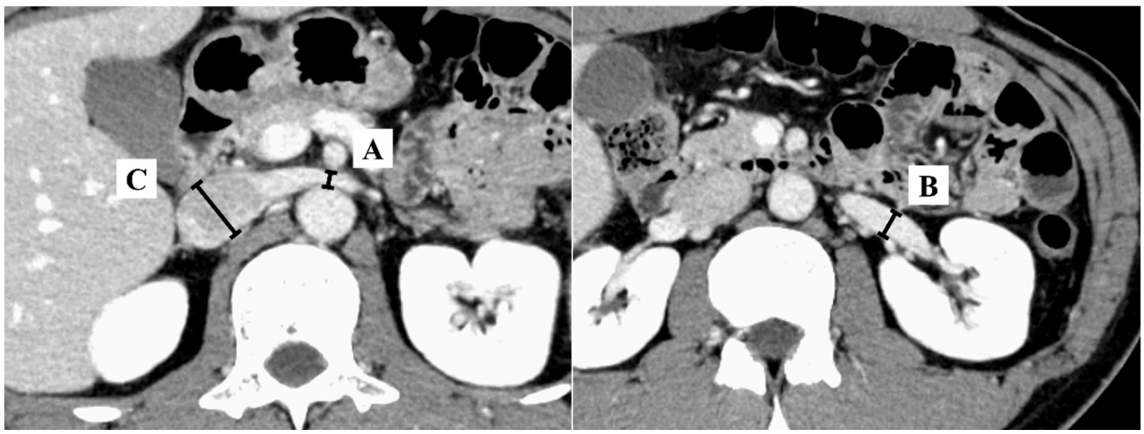

Figure 3. In the control group (non-heart failure group), the distance between the aorta and the superior mesenteric artery (A) and the maximum diameter of the left renal vein (B) and inferior vena cava (C) were also measured as anatomical measurements of renal vasculature on contrast-enhanced axial CT images.

2.4. Statistical Analyses

The normality of continuous variables was assessed using the Shapiro–Wilk test and visual inspection of Q-Q plots. Data with normal distribution were expressed as mean ± standard deviation, and data with skewed distribution are presented as median with interquartile range. The unpaired *t*-test (for normally distributed data) or the Mann–Whitney U test (for non-normally distributed data) was used to compare age, kidney volumes, aorta-SMA distance and the maximum diameters of the left renal vein and IVC between the large right kidney group and the large left kidney group, as well as between the non-heart failure group and the heart failure group. Differences between sexes were compared using the chi-square test. The Wilcoxon signed rank test was used to compare the right and left kidney volumes within the heart failure group. Kidney volumes, the difference in kidney volume (left–right) and eGFR between the initial CT and the follow-up CT within the increased or decreased cardiac width group were compared using the paired *t*-test (for normally distributed data) or the Wilcoxon signed rank test (for non-normally distributed data). The unpaired *t*-test was used to compare the follow-up CT findings between patients with a follow-up period of ≤2 months and >2 months within the decreased cardiac width group. Differences were considered statistically significant at $p < 0.05$. *p* values for the between-group differences are nominal *p* values without multiplicity adjustment. All statistical analyses were performed using the JMP software program (version 19; JMP Statistical Discovery LLC, Cary, NC, USA). Heart failure and control groups were not matched, and intergroup comparisons were not adjusted for potential confounders.

3. Results

3.1. Kidney Volume Asymmetry in the Non-Heart Failure Group

The relationship between total kidney volume and eGFR is shown in Figure 4. In the non-heart failure group ($n = 147$), the left kidney volume was significantly larger than the right kidney volume (134 [46] mL vs. 127 [42] mL, $p < 0.0001$), highlighting a consistent

asymmetry in kidney volumes within the non-heart failure group. Stratification into the large right kidney group ($n = 46$) and the large left kidney group ($n = 101$) revealed no significant differences in total kidney volume or right kidney volume between groups. However, the left kidney volume was significantly larger in the large left kidney group (125 ± 27 mL vs. 141 ± 33 mL, $p = 0.005$). Although the large left kidney group tended to exhibit a narrower aorta/SMA distance and a larger left renal vein diameter, these differences did not reach statistical significance (Table 1).

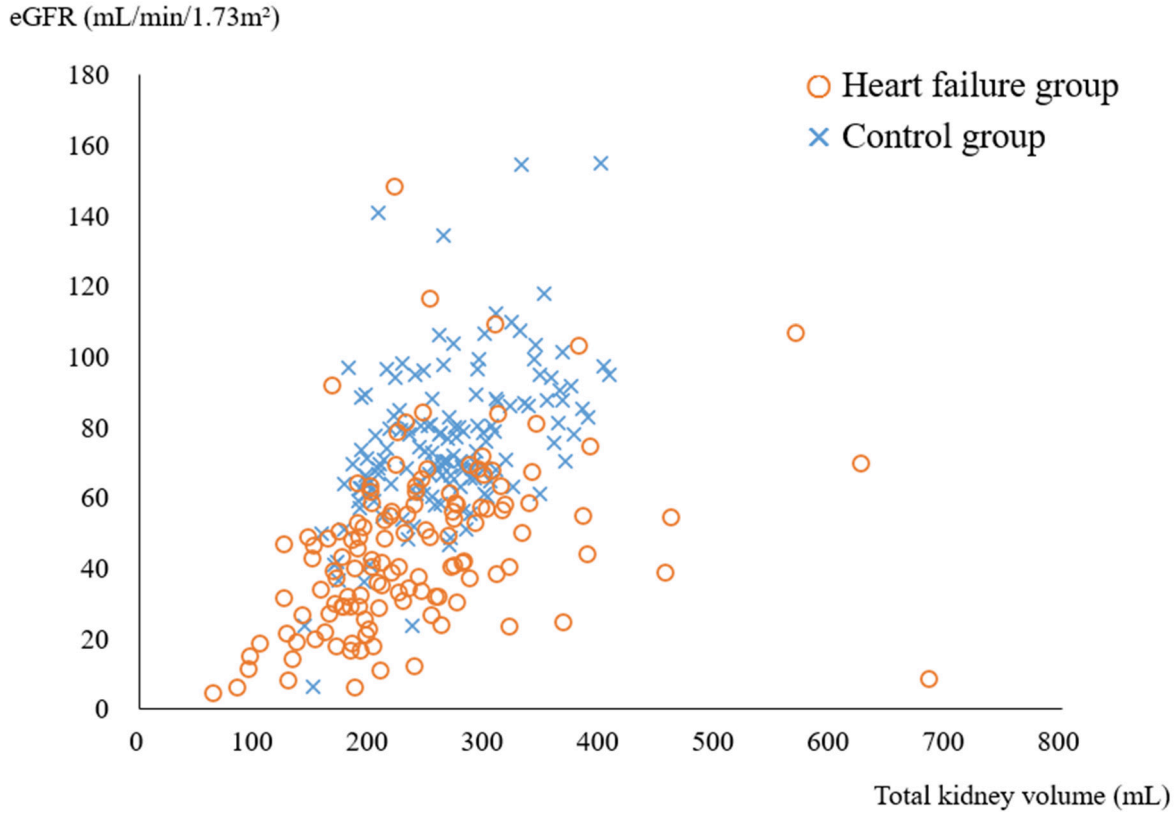

Figure 4. The relationship between total kidney volume and eGFR.

Table 1. Comparison of kidney volumes, distance and maximum diameter between the large right kidney group and the large left kidney group within the non-heart failure group.

	Large Right Kidney Group ($n = 46$)	Large Left Kidney Group ($n = 101$)	*p* Value
Age (years)	69 (17.5)	69 (17.5)	0.9717
Sex (male/female) *	24/22	61/40	0.3493
Total kidney volume (mL)	261 ± 54	267 ± 61	0.5899
Right kidney volume (mL)	137 ± 28	126 ± 29	0.0511
Left kidney volume (mL)	125 ± 27	141 ± 33	0.0050
Aorta/SMA distance (mm)	13.2 (9.3)	10.6 (9.3)	0.1920
Maximum diameter of the left renal vein (mm)	9.8 ± 1.7	10.5 ± 2.1	0.0504
Maximum diameter of IVC (mm)	15.6 ± 5.3	15.7 ± 5.5	0.9117

Unless otherwise specified, data are means ± standard deviations or medians with interquartile ranges in parentheses. * Data are numbers of patients. SMA = superior mesenteric artery, IVC = inferior vena cava.

3.2. Comparison of Kidney Volumes Between Heart Failure and Non-Heart Failure Patients

When comparing the two study groups, patients with heart failure exhibited significantly reduced total kidney volumes compared with the non-heart failure group (224 [96] mL vs. 263 [84] mL, $p < 0.0001$). Both right and left kidney volumes were

also significantly smaller in heart failure patients (109 [48] mL vs. 127 [42] mL, $p = 0.0002$; and 114 [57] mL vs. 134 [46] mL, $p < 0.0001$, respectively) (Table 2).

Table 2. Comparison of total, right and left kidney volumes between the non-heart failure group and the heart failure group.

	Non-Heart Failure Group ($n = 147$)	Heart Failure Group ($n = 131$)	*p* Value
Total kidney volume (mL)	263 (84)	224 (96)	<0.0001
Right kidney volume (mL)	127 (42)	109 (48)	0.0002
Left kidney volume (mL)	134 (46)	114 (57)	<0.0001

Data are medians with interquartile ranges in parentheses.

3.3. Differences Between Right and Left Kidney Volume in the Heart Failure Group

In the heart failure group ($n = 131$), no statistically significant difference was observed between the right and left kidney volumes ($p = 0.482$). Within the heart failure group, further stratification by renal function (estimated glomerular filtration rate; eGFR) revealed consistent tendencies, although neither laterality comparison reached statistical significance. In patients with an eGFR ≥ 30 mL/min/1.73 m^2 ($n = 97$), the left kidney volume tended to be larger than the right ($p = 0.0568$). In contrast, patients with an eGFR < 30 ($n = 34$), the left kidney volume tended to be reduced compared with the right ($p = 0.0564$), although this numerical difference was not statistically significant (Table 3).

Table 3. Comparison of right and left kidney volumes based on renal function (eGFR) within the heart failure group.

Heart Failure Group	Right Kidney Volume (mL)	Left Kidney Volume (mL)	*p* Value
eGFR ≥ 30 ($n = 97$)	119 (45)	125 (53)	0.0568
eGFR < 30 ($n = 34$)	92 (28)	86 (35)	0.0564

Data are medians with interquartile ranges in parentheses.

3.4. Longitudinal Changes in Kidney Volume and Renal Function

Of 131 patients with heart failure, 54 underwent follow-up CT scans. The follow-up period ranged from 2 to 798 days, with an average of 144.2 days. The follow-up group was divided into an increased cardiac width group ($n = 20$) (2–564 days, average: 117.0 days) and a decreased cardiac width group ($n = 34$) (4–798 days, average: 159.7 days).

Among the increased cardiac width group, total kidney volume increased significantly between the initial and follow-up CT scans (227 ± 52 to 252 ± 60 mL, $p < 0.0001$). Both right and left kidney volumes increased significantly, with a more pronounced increase in the left kidney, leading to a larger left-right difference ($p = 0.0180$) (Figure 5). eGFR did not change significantly ($p = 0.7417$) (Table 4).

Table 4. Comparison of kidney volumes and eGFR between the initial CT and the follow-up CT within the increased cardiac width group ($n = 20$).

	Initial CT	Follow-Up CT	*p* Value
Total kidney volume (mL)	227 ± 52	252 ± 60	<0.0001
Right kidney volume (mL)	110 ± 22	120 ± 25	0.0006
Left kidney volume (mL)	117 ± 31	130 ± 36	<0.0001

Table 4. *Cont.*

	Initial CT	Follow-Up CT	*p* Value
Difference in kidney volume (left–right) (mL)	6.8 ± 15.7	9.7 ± 16.8	0.0180
eGFR (mL/min/1.73 m^2) (n = 19)	48.6 (34.8)	48.7 (35.5)	0.7417

Data are means ± standard deviations or medians with interquartile ranges in parentheses. eGFR = estimated glomerular filtration rate, CT = computed tomography.

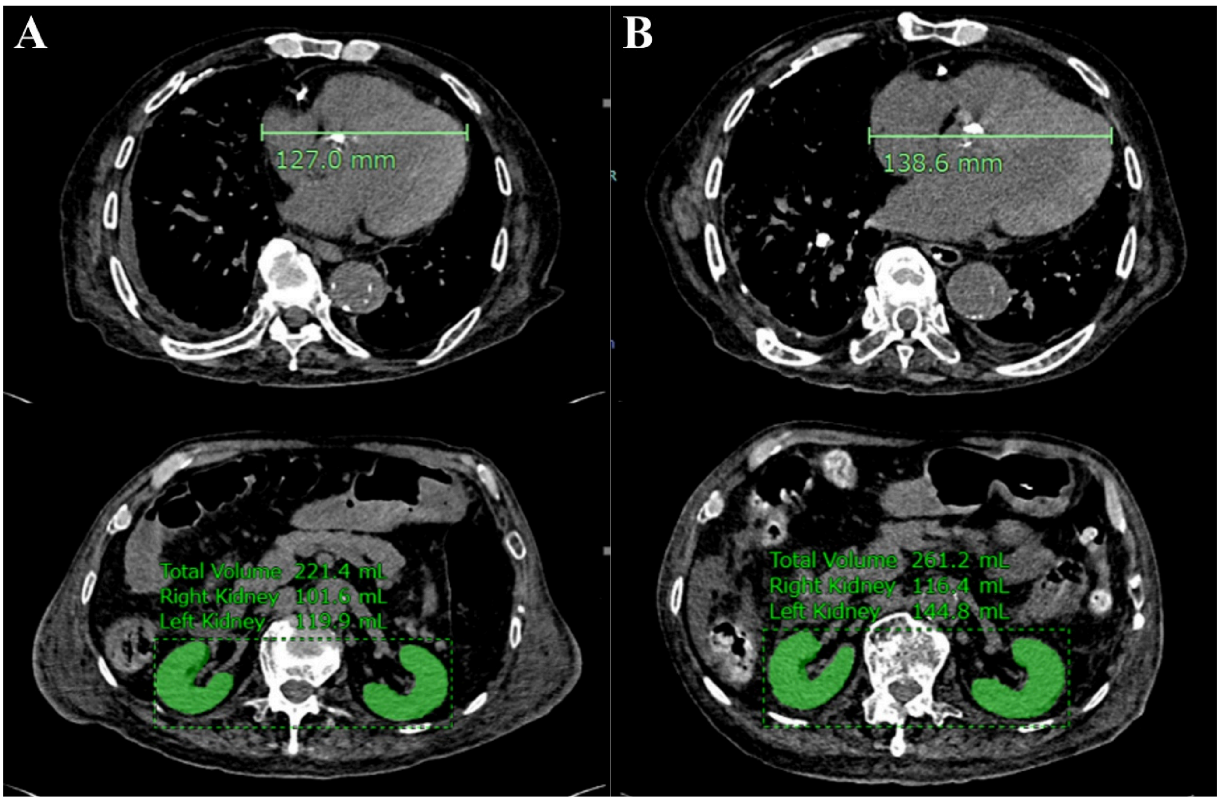

Figure 5. In the increased cardiac width group, total kidney volume significantly increased between the initial (**A**) and follow up (**B**) CT images.

In the decreased cardiac width group (n = 34), total kidney volume decreased significantly between initial and follow-up CT scans (246 ± 76 to 228 ± 72 mL, $p < 0.0001$). Both right and left kidney volumes showed significant reductions, while the left-right difference remained nonsignificant ($p = 0.1668$) (Figure 6). eGFR increased during follow-up ($p = 0.0316$) (Table 5).

Table 5. Comparison of kidney volumes and eGFR between the initial CT and the follow-up CT within the decreased cardiac width group (n = 34).

	Initial CT	Follow-Up CT	*p* Value
Total kidney volume (mL)	246 ± 76	228 ± 72	<0.0001
Right kidney volume (mL)	123 ± 40	115 ± 37	0.0009
Left kidney volume (mL)	123 ± 38	113 ± 35	<0.0001
Difference in kidney volume (left–right) (mL)	0.4 (12.2)	−1.8 (14.6)	0.1668
eGFR (mL/min/1.73 m^2) (n = 29)	44.1 ± 20.2	50.4 ± 22.8	0.0316

Data are means ± standard deviations or medians with interquartile ranges in parentheses. eGFR = estimated glomerular filtration rate, CT = computed tomography.

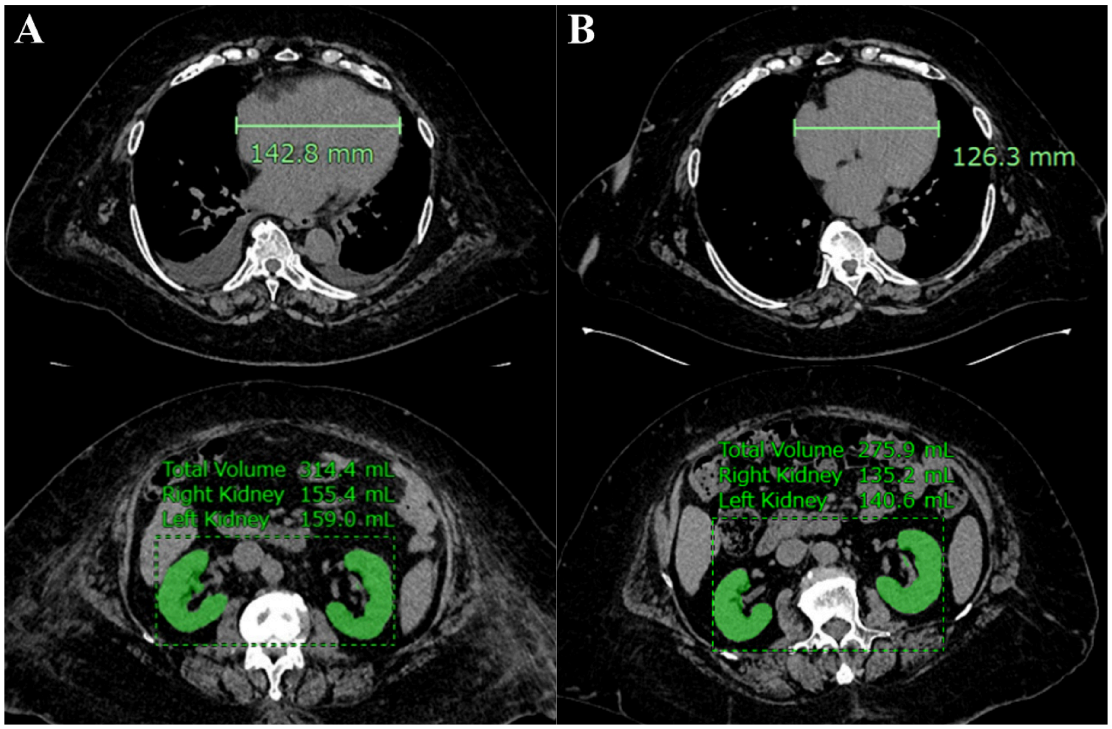

Figure 6. In the decreased cardiac width group, total kidney volume significantly decreased between the initial (**A**) and follow up (**B**) CT scans.

3.5. Effect of Follow-Up Period on Kidney Volume Changes in the Decreased Cardiac Width Group

In the subgroup analysis of the decreased cardiac width group, patients with a follow-up period of ≤2 months ($n = 15$) and >2 months ($n = 19$) showed no significant differences in total or unilateral kidney volumes ($p = 0.8935$, 0.8158, and 0.9826, respectively). Similarly, no significant difference in laterality was observed ($p = 0.5207$), although the >2-month subgroup exhibited a trend toward more pronounced left kidney atrophy (Table 6).

Table 6. Comparison of follow-up CT findings between patients with a follow-up period of ≤2 months and >2 months within the decreased cardiac width group ($n = 34$).

	Patients with a Follow-Up Period of ≤2 Months ($n = 15$)	Patients with a Follow-Up Period of >2 Months ($n = 19$)	*p* Value
Total kidney volume (mL)	226 ± 94	230 ± 51	0.8935
Right kidney volume (mL)	114 ± 51	117 ± 24	0.8158
Right kidney volume change (mL)	−10.1 ± 13.5	−6.2 ± 12.1	0.3792
Left kidney volume (mL)	113 ± 44	113 ± 28	0.9826
Left kidney volume change (mL)	−12.5 ± 13.2	−8.6 ± 10.8	0.3471
Difference in kidney volume (left–right) (mL)	−0.7 ± 12.1	−3.6 ± 12.9	0.5207

Data are means ± standard deviations. Right/left kidney volume change (mL) = Volume in follow-up CT—Volume in initial CT. CT = computed tomography.

4. Discussion

The present study utilized fully automated 3D CT volumetry to assess kidney volumes and their relationships with heart failure and renal function. The accuracy and reproducibility of commercially available automated 3D CT segmentation have been examined in previous studies. Therefore, this method is clinically applicable, and has been widely used in routine CT examinations [9–11,15]. Regarding efficiency, the previous study using prototype automated CT volumetry showed that the average total time for automated CT volumetry was substantially shorter than that for manual volumetry and semi-automated

volumetry [16]. Our findings describe renal volume differences in heart failure and changes associated with cardiac width; the underlying mechanisms remain uncertain. These observations may help guide future studies on cardiorenal interactions [17].

In the non-heart failure group, the left kidney volume was significantly larger than the right kidney volume, suggesting an inherent asymmetry in renal anatomy [4,18]. Additionally, the left kidney volume was significantly larger in the large left kidney group than in the large right kidney group, suggesting that changes in the left kidney volume are a major factor contributing to the observed asymmetry. The left kidney is located further from the IVC and has a longer renal venous pathway crossing the aorta. Interestingly, the subgroup with greater left kidney volume exhibited trends toward narrower Ao/SMA distances (physiological narrowing) and larger left renal vein diameters, indicative of variations in vascular anatomy. Although these differences were not statistically significant, they may influence renal perfusion and susceptibility to congestion under pathophysiological conditions.

Comparisons between the non-heart failure and heart failure groups revealed significant reductions in kidney volumes among heart failure patients, consistent with prior reports linking reduced kidney volume to CKD progression [5,19]. However, these unadjusted differences may also reflect age and other clinical factors, rather than heart failure alone.

The subgroup analysis within the heart failure cohort revealed consistent tendencies based on renal function. In patients with an eGFR ≥ 30, the left kidney volume tended to be larger than the right, potentially attributable to renal congestion secondary to elevated venous pressures in the acute phase of heart failure [5,20]. Elevated central venous pressure has been associated with impaired renal function in heart failure [21]. Our nonsignificant laterality findings are exploratory and do not establish an early marker of CRS progression. Conversely, in patients with an eGFR < 30, left kidney volume was numerically smaller, but not significantly so. A relationship between these patterns and chronic renal damage remains hypothetical [22]. Previous studies have identified venous congestion as a critical determinant of renal dysfunction in heart failure, further emphasizing the dynamic interplay between right ventricular overload and renal congestion.

Follow-up CT data provided additional insights into the volumetric changes in kidney and renal function. In the increased cardiac width group, increases in both right and left kidney volumes were observed with a larger left-right difference, possibly reflecting changes in renal congestion, although this was not directly evaluated [2,23,24]. There was no significant change in eGFR ($p = 0.7417$).

In contrast, in the decreased cardiac width group, the total renal volume decreased significantly during follow-up, particularly in the left kidney. Reduced renal congestion is one possible explanation, but this was not directly measured. Kidney volume changes did not differ significantly between the follow-up interval subgroups (Table 6). This finding aligns with previous reports that chronic renal hypoperfusion and venous hypertension can result in renal fibrosis and atrophy over time [25,26]. These findings highlight the importance of managing venous pressures and fluid status in mitigating renal damage in heart failure patients.

From a clinical perspective, the observed relationships between kidney volume, renal function, and heart failure progression have several implications. First, automated 3D CT volumetry may provide complementary structural information, but its prognostic utility is unproven. Second, a possible relation to renal congestion warrants further hemodynamic evaluation [23,27]. Third, the observed patterns may reflect heterogeneity in CRS, although their clinical significance is uncertain. The eGFR is a simple index of renal function, while CT volumetry provides complementary structural measurements. Whether adding CT volumetry to eGFR improves clinical evaluation remains to be determined.

Several limitations of this study must be acknowledged. First, the sample size of the subgroups was relatively small, which may limit the generalizability of the findings. The CT-selected cohorts were not matched or adjusted for confounders, including age. Second, the reliance on CT imaging for renal volume assessment may not capture functional changes at the microvascular level. Diffusion-weighted or multiparametric renal MRI may help assess renal tissue abnormalities, including fibrosis, whereas Doppler ultrasound can provide hemodynamic information [23,28]. Third, only 54 of 131 patients (41.2%) underwent follow-up CT scans, and the follow-up periods varied widely among cases, raising concerns about selection bias. Clinically indicated repeat CT may preferentially include patients with more complex illness, introducing further selection bias. Future studies will be needed to examine a larger group of patients who underwent CT scans with a consistent follow-up period. Fourth, regarding the laterality of kidney volume in this study, the anatomical explanation alone is insufficient for selective left kidney involvement. The laterality differences were nonsignificant, and no prognostic model was tested. Other causes such as hemodynamic factors and neural regulation differences should be considered and clarified in future studies. Additionally, congestion and atrophy cannot be established from these associations without hemodynamic or pathological confirmation. Cardiac width was not validated against serial echocardiography, natriuretic peptides, clinical status, or venous pressure. Finally, although we observed trends and significant findings related to kidney volume and CRS, the pathophysiological mechanisms remain speculative and warrant further experimental and clinical studies.

In conclusion, this study using a fully automated 3D CT volumetry of the kidney with a deep learning algorithm highlights the dynamic changes in renal volume and function in patients with heart failure, providing valuable insights into the pathophysiology of CRS. The nonsignificant left–right differences are hypothesis-generating and require I have checked. prospective validation. Further studies should determine whether renal volume provides clinically useful information beyond conventional measures.

Author Contributions: Conceptualization, K.I.; methodology, M.H.; formal analysis, M.T.; investigation, Y.K., H.K., H.F. and J.I.; data curation, N.K. and K.N.; writing—original draft preparation, N.K.; writing—review and editing, M.T., M.H., Y.K., H.K., H.F., J.I. and K.I.; supervision, K.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Yamaguchi University Hospital (protocol code 2025-056, approved on 18 June 2025).

Informed Consent Statement: Patient consent was waived due to the retrospective nature of this research.

Data Availability Statement: The datasets generated or analyzed during the study are available from the corresponding author on reasonable request due to ethical restrictions; access requires approval from the institutional ethics committee.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CKD	chronic kidney disease
CRS	cardiorenal syndrome
CT	computed tomography
eGFR	estimated glomerular filtration rate
GFR	glomerular filtration rate

IVC	inferior vena cava
SMA	superior mesenteric artery
3D	three-dimensional

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