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Kidney volume measurement and predictive modeling in children aged 0–18 years using a computer-assisted surgery system

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This study aimed to measure the normal renal volume in children and adolescents aged 0–18 years from the eastern coastal region of China using the computer-assisted surgery (CAS) system. Accurate measurement of kidney volume is important as a marker for follow-up in patients with congenital anomalies. We established reference ranges for renal volume based on age, height, and weight, and developed predictive models using commonly available clinical data. A total of 803 children and adolescents participated, with clinical data including age, gender, height, weight, body mass index (BMI) and body surface area (BSA) collected. The Hisense CAS system was employed to perform 3D reconstructions of CT images, allowing precise measurement of left and right kidney volumes. Statistical analysis revealed a significant difference in size between the left and right kidneys ($P < 0.01$), with the left kidney being larger in 79.08% of cases. Age, height, weight, BMI, and BSA were all significantly correlated with kidney volume, with BSA showing the strongest correlation. We developed predictive formulas based on height and weight with good accuracy ($R^2 = 0.896$ for left kidney and $R^2 = 0.891$ for right kidney). These findings provide reference values for renal volume and offer useful tools for early detection and monitoring of renal abnormalities in the pediatric population.

Keywords Kidney volume, Children, Computer-assisted surgery, 3D reconstruction

Renal volume is a critical clinical parameter, with many kidney diseases and treatments associated with changes in kidney size. For instance, conditions such as congenital kidney abnormalities, polycystic kidney disease, and post-nephrectomy follow-up all involve renal volume as a key factor[1,2]. Additionally, Smaller kidney volumes and higher blood pressure are associated with increased albuminuria, further supporting the connection between kidney volume and long-term kidney health. This highlights the need to measure renal volume in order to evaluate kidney function in children and detect kidney disease early, which is essential for developing preventive strategies[3–5]. While kidney volume in children is known to be influenced by race, there is limited reference data for normal renal volume in Chinese children across various age groups[3].

Clinically, kidney morphology is still commonly described using measurements of kidney length, width, and height, which require complex calculations based on assumptions about kidney shape[6–8]. With advancements in three-dimensional(3D) imaging technology, there has been growing interest in accurately measuring kidney volume and virtually reconstructing kidney morphology. However, the accuracy of ultrasound-based kidney volume measurements remains debated[9]. The computer-assisted surgery (CAS) system can perform 3D reconstructions of enhanced CT images in pediatric patients and automatically provide precise renal volume measurements.

This study aims to use the CAS system to measure normal kidney volume parameters in children, establish reference ranges for renal volume across different age, height, and weight, and develop predictive models using commonly available clinical data, such as height and weight.

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Materials and methods

Study design and patients

In this retrospective study, we collected data from 803 pediatric patients aged 0–18 years who were treated between December 2012 and July 2022 for hepatic or pancreatic diseases, such as hepatoblastoma, or other non-renal conditions that did not involve the kidneys. The cohort consisted of 438 females and 365 males. All patients underwent dynamic contrast-enhanced abdominal CT scans, and their imaging data were reconstructed in 3D using the Hisense CAS system.

Inclusion criteria: (1) Exclusion of premature infants and children who are small for their age; (2) No history of renal disease or other major conditions affecting kidney volume (e.g., renal failure, renal tumors); (3) Absence of urinary tract malformations, acute or chronic urinary tract infections, hereditary metabolic disorders, endocrine disorders, or congenital heart disease, which could potentially impact renal growth and development; (4) No evidence of kidney deformation due to intra-abdominal tumors (e.g., intra-abdominal cysts, teratomas); (5) Availability of clear contrast-enhanced CT images along with complete clinical data, including gender, height, weight, body surface area, and body mass index; (6) Informed consent was obtained from the children and their legal guardians, who voluntarily agreed to participate in the study.

Basic clinical information, including age (months/years), height (cm), weight (kg), and kidney volume (cm^3), was collected. The study was approved by the Ethics Committee of the Affiliated Hospital of Qingdao University (Approval No. QYFY WZLL 29043). All experiments were performed in accordance with relevant guidelines and regulations.

Equipment and materials

Abdominal contrast-enhanced CT scanning equipment

The following CT scanners were utilized: GE DISCOVERY CT750HD 64-slice spiral CT (USA); GE BRIGHTSPEED ELITE 16-slice CT (USA); Philips MX4000 dual-slice spiral CT (Netherlands); and Siemens SOMATOM Sensation Cardiac 64-slice CT (Germany).

Hisense computer assisted surgery system (Hisense CAS)

Model: JI-GEMI-MS4, System Version: CAS V4.02. The Hisense CAS, a computer-assisted surgery system, was developed in collaboration between the Affiliated Hospital of Qingdao University and Hisense Medical Group, under the support of China's National "Twelfth Five-Year" Science and Technology Project.

Non-Ionic contrast agent

Iopromide injection (100 mL : 35 g I) (Beijing Beilu Pharmaceutical Co., Ltd.), with the National Drug Standard Number: H20053800.

Formulas for body surface area (BSA) and body mass index (BMI)

BSA (m^2) = 0.024265 * Weight (kg) $^{0.5378}$ *Height (cm) $^{0.3964}$(Haycock formula)[10];

BMI (kg/m^2) = Weight (kg) / Height² (m)[11].

Formulas for BSA-adjusted kidney volume

$$\text{BSA} - \text{Adjusted Left Kidney Volume (BSA\_adjusted\_LK)} \ \left(\text{cm}^3/\text{m}^2\right) = \text{Left Kidney Volume} \ \left(\text{cm}^2\right)/\text{BSA} \ \left(\text{m}^2\right)$$

$$\text{BSA} - \text{Adjusted Right Kidney Volume (BSA\_adjusted\_RK)} \ \left(\text{cm}^3/\text{m}^2\right) = \text{Right Kidney Volume} \ \left(\text{cm}^3\right)/\text{BSA} \ \left(\text{m}^2\right)$$

$$\text{BSA} - \text{Adjusted Total Kidney Volume (BSA\_adjusted\_TK)} \ \left(\text{cm}^3/\text{m}^2\right) = \text{Total Kidney Volume} \ \left(\text{cm}^3\right)/\text{BSA} \ \left(\text{m}^2\right)$$

These formulas normalize kidney volumes to body surface area, providing a standardized measure to account for variations in body size among individuals.

Research methods

Abdominal dynamic contrast-enhanced CT examination

Before the examination, patients were instructed to fast for 4–6 h, and an intravenous line was established for the injection of iodinated contrast medium (Iohexol). For uncooperative children, 0.5 mg/kg of chloral hydrate was administered via rectal enema. The child was positioned supine on the CT examination table, ensuring the body was straight, with the head resting on a headrest and both hands raised above the head to maintain stillness. The operator positioned the CT table over the upper abdomen, scanning from the diaphragm to the umbilicus, with the scan direction from head to foot. The arterial phase delay was set to 25 s, and the portal venous phase delay was set to 50 s. Finally, the image data were uploaded and stored in the workstation in DICOM format.

3D reconstruction of the kidney using hisense CAS

(1) The DICOM files of the thin-slice CT scans were imported into the Hisense CAS system for processing.
(2) Window width and level were adjusted, and kidney edges were precisely segmented in the equilibrium phase using a region-growing segmentation algorithm. The segmentation results were verified by overlaying a transparent mask on the original image data, with interactive tools for local adjustments. Accurate kidney volume measurements were then calculated by combining the segmentation results with imaging scan parameters, such as pixel spacing and slice thickness. The results, along with an interactive 3D reconstruction image with full rotational capability, were displayed in the window.

(3) To ensure the accuracy of the segmentation, the segmented areas of interest on the CT images were compared with the corresponding areas on the 3D kidney model. Each case was reviewed and verified by at least two experienced pediatric surgeons with over five years of experience and one radiologist with over ten years of experience. The inter-observer reliability was maintained through consistent calibration and regular training for the medical staff involved in the review process.

Statistical analysis methods

Data analysis was performed using SPSS version 29.0. The normality of continuous variables was first assessed with the Shapiro-Wilk test. Normally distributed data were expressed as mean ± standard deviation ($\bar{x}$±s) and compared between groups using the t-test. Non-normally distributed data were presented as the median (range) [M(P25, P75)] and compared between groups using the Mann–Whitney U test. Categorical data were expressed as percentages (%).

For the reference ranges of renal volume in different groups, if the data were normally distributed, the reference range was estimated using "mean ± 1.96 × standard deviation"; for non-normally distributed data, the reference range was determined using percentiles (e.g., 5th and 95th percentiles).

The correlation between renal volume and age, height, weight, and gender was analyzed using Pearson correlation analysis. Multiple linear regression was employed to obtain correlation coefficients and regression equations.

All analyses were considered statistically significant at $P < 0.05$.

Results

Clinical baseline data and 3D reconstruction outcomes

A total of 803 children were included in the study, and their clinical data, including age, gender, height, weight, body surface area (BSA), and body mass index (BMI), were collected, as detailed in Table 1.

Using the Hisense CAS system, 3D reconstruction of the CT images was performed to obtain the bilateral kidney volumes for each child. The reconstructed images are illustrated in Fig. 1.

Comparison of left and right kidney volumes

Paired t-tests were conducted to compare the volumes of the left and right kidneys in each child. The results revealed a statistically significant difference between the two sides ($P < 0.01$). Specifically, in 635 cases (79.08%), the left kidney was larger than the right. The detailed statistics are presented in Supplementary Table S1.

Correlation analysis between kidney volume and clinical baseline characteristics

Correlation of age, height, weight, BSA, and BMI with kidney volume

We analyzed the correlations between age, height, weight, BSA, and BMI with the volumes of the left, right, and total kidneys. The results are summarized in Table 2 (descriptive statistics) and Table 3 (correlation analysis). The analysis showed that BSA had the highest correlation with kidney volume, while BMI had the lowest.

Differences in kidney volume between genders within the same age group

We compared kidney volumes between boys and girls within the same age group. No statistically significant differences were observed between the genders across all age groups ($P > 0.05$). Generally, boys tended to have slightly larger kidney volumes than girls, as shown in Supplementary Table S2.

Reference ranges for kidney volume based on different groupings

Given that age, height, and weight are clinically accessible and straightforward metrics, we established reference ranges for kidney volume by grouping based on these three indicators, as shown in Supplementary Table S3.

Age(m\y)	*n*	Sex		Height (cm)	Weight (kg)	BMI (kg/m^2)	BSA (m^2)
		Male	Female				
0–3(m)	60	30	30	55.38 ± 4.73	4.98 ± 1.14	16.09 ± 2.18	0.25 ± 0.04
3–6	39	19	20	65.68 ± 7.06	7.31 ± 0.98	17.27 ± 3.04	0.34 ± 0.05
6–12	67	31	36	69.99 ± 4.72	8.77 ± 1.51	17.89 ± 2.59	0.39 ± 0.04
1–2(y)	67	29	38	80.12 ± 5.71	10.81 ± 1.58	16.86 ± 1.97	0.47 ± 0.05
2–4	91	36	55	95.15 ± 6.02	14.00 ± 2.26	15.47 ± 2.01	0.61 ± 0.06
4–6	70	38	32	108.58 ± 7.73	18.42 ± 3.57	15.55 ± 1.98	0.75 ± 0.09
6–8	65	31	34	124.60 ± 6.41	24.94 ± 5.94	15.92 ± 2.84	0.93 ± 0.11
8–10	65	30	35	137.23 ± 6.34	31.44 ± 7.98	16.58 ± 3.33	1.09 ± 0.13
10–12	66	29	37	148.19 ± 9.01	37.94 ± 10.09	17.12 ± 3.27	1.24 ± 0.17
12–14	76	37	39	159.43 ± 11.97	51.30 ± 15.80	19.96 ± 4.73	1.48 ± 0.25
14–16	38	17	21	168.58 ± 8.54	60.50 ± 14.16	21.17 ± 4.31	1.65 ± 0.21
16–18	99	38	61	168.70 ± 7.40	60.79 ± 12.67	21.29 ± 3.82	1.65 ± 0.19

Table 1. Clinical characteristics of the included children.

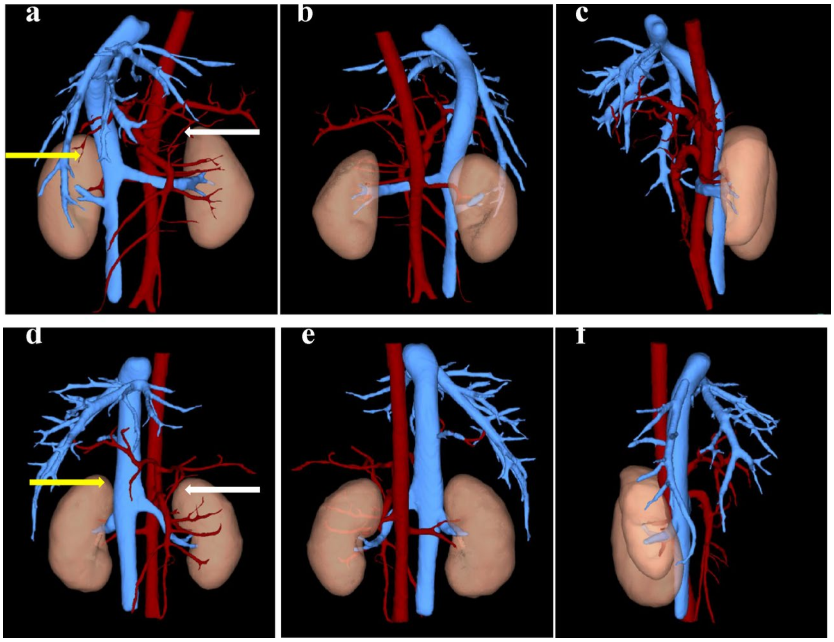

Fig. 1. Three-dimensional reconstructions of the kidneys in two children.(Image created using Hisense CAS software, version 4.02.). (**a**–**c**): A 6-year and 7-month-old female child, shown from the anterior, posterior, and lateral views, where the kidneys appear smaller and more rounded; (**d**–**f**) an 11-year and 4-month-old male child, shown from the anterior, posterior, and lateral views, where the kidneys exhibit a more adult-like morphology. The white arrows indicate the renal arteries, and the yellow arrows indicate the renal veins.

Variable	Mean ± standard deviation
Age (m)	87.08 ± 71.23
Height (cm)	117.34 ± 39.61
Weight (kg)	28.45 ± 21.46
BMI (kg/m^2)	17.60 ± 3.72
BSA (m^2)	0.94 ± 0.51
Left Kidney volume (cm^3)	86.29 ± 52.55
Right Kidney volume (cm^3)	81.81 ± 49.50
Total Kidney volume (cm^3)	168.10 ± 101.72

Table 2. Descriptive statistics of study variables.

Variable	Left kidney volume (cm^3)	Right kidney volume (cm^3)	Total kidney volume (cm^3)
Age (m)	$r^* = 0.924$, $p^{**} < 0.001$	$r = 0.920$, $p < 0.001$	$r = 0.925$, $p < 0.001$
Height (cm)	$r = 0.924$, $p < 0.001$	$r = 0.921$, $p < 0.001$	$r = 0.925$, $p < 0.001$
Weight (kg)	$r = 0.925$, $p < 0.001$	$r = 0.923$, $p < 0.001$	$r = 0.927$, $p < 0.001$
BMI (kg/m^2)	$r = 0.519$, $p < 0.001$	$r = 0.519$, $p < 0.001$	$r = 0.521$, $p < 0.001$
BSA (m^2)	$r = 0.946$, $p < 0.001$	$r = 0.943$, $p < 0.001$	$r = 0.948$, $p < 0.001$

Table 3. Correlation of kidney volume with age, height, weight, BMI, and BSA. *r: Pearson correlation coefficient; ***p*-value.

To standardize kidney volume measurements, we adjusted for body size by calculating the BSA-adjusted kidney volumes for the left (BSA_adjusted_LK), right (BSA_adjusted_RK), and total kidneys (BSA_adjusted_TK). These adjustments were done by dividing the measured kidney volumes by the body surface area (BSA), which accounts for variations in body size across individuals. The standardized kidney volumes were calculated and grouped by age, with the mean and standard deviation for each group provided in Supplementary Table S4.

Development of a pediatric kidney volume prediction model

Given the strong correlation between kidney volume and the factors of age, height, and weight, as identified in "Correlation of age, height, weight, BSA, and BMI with kidney volume" section, and considering that these parameters are easily obtainable in clinical practice, we established a pediatric kidney volume prediction model incorporating these three variables.

Multiple linear regression model

Initially, scatter plots were generated to visualize the relationships between age, height, and weight with kidney volumes for both kidneys (Fig. 2). The plots indicate a clear positive linear correlation between these variables and kidney volume.

Based on these observations, a stepwise multiple linear regression analysis was conducted with kidney volume as the dependent variable and age, height, and weight as independent variables. Three models were generated, as detailed in in Supplementary Table S5. However, high collinearity (VIF > 10) was observed when all three variables were included, prompting us to exclude age, the variable with the highest VIF, from the final models. The resulting predictive models for left and right kidney volumes are as follows:

Left Kidney Volume: Y = – 22.427 + 0.636 × Height + 1.200 × Weight (cm^2) (R^2 = 0.896; $P < 0.01$);Right Kidney Volume: Y = – 19.522 + 0.585 × Height + 1.149 × Weight (cm^2) (R^2 = 0.891; $P < 0.01$).

Model validation

To assess the applicability and accuracy of the regression models, we visualized the results through residual plots (Fig. 3a–b), prediction interval plots (Fig. 3c–d), and Bland-Altman plots (Fig. 3e–f). The residual plots show a random distribution of scatter points around the red dashed line, indicating that the linear regression models are appropriate for the data. The prediction interval plots demonstrate that most actual values fall within the confidence intervals, and the predicted value curves closely follow the actual values, suggesting high model reliability. The Bland-Altman plots reveal that most points fall within the limits of agreement, with an average difference close to zero, indicating good consistency between the predicted and actual values.

Discussion

This study aimed to analyze kidney volumes and clinical baseline data in children and adolescents aged 0–18 years from the eastern coastal region of China. We established reference values for kidney volumes in this population, categorized by age, height, and weight. We also developed predictive formulas based on commonly available clinical parameters, which have practical value for clinical use.

Kidney volume is closely associated with various renal conditions, such as congenital renal anomalies, polycystic kidney disease, and urinary tract infections[12]. Accurate kidney volume measurements help clinicians detect these conditions early, improving treatment and prognosis. Many studies have calculated kidney volume

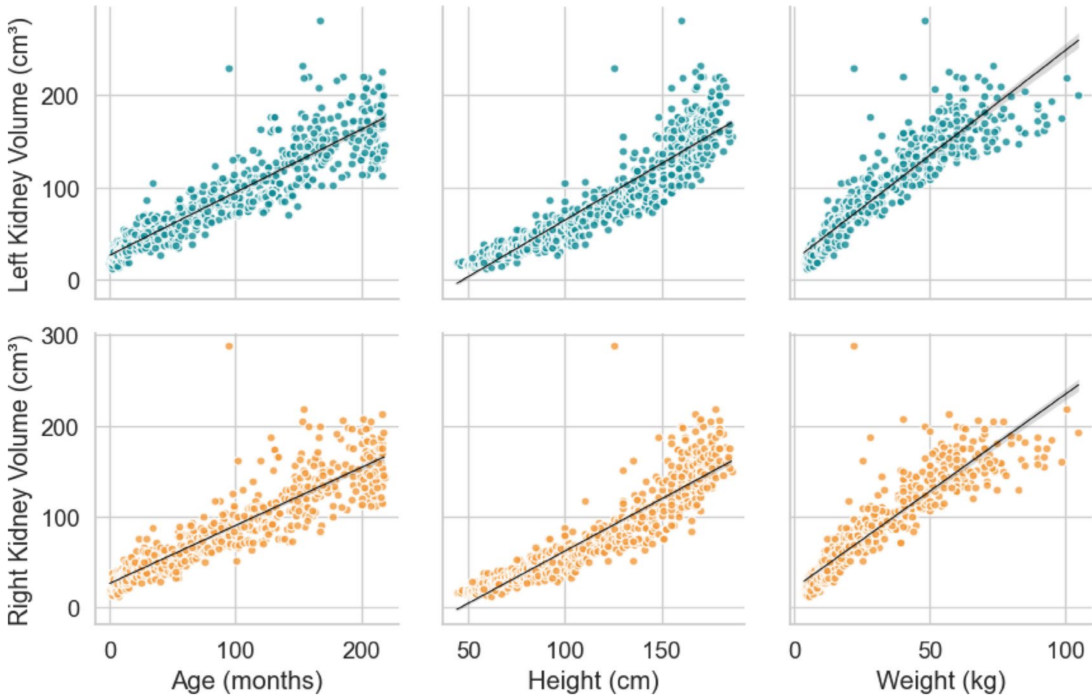

Fig. 2. Scatter matrix of kidney volumes against age, height, and weight. The scatter plots show the relationship between left kidney volume (top row, teal) and right kidney volume (bottom row, orange) with age, height, and weight. Each point represents an individual subject, and the regression lines indicate the positive linear correlation between the respective variables and kidney volume.

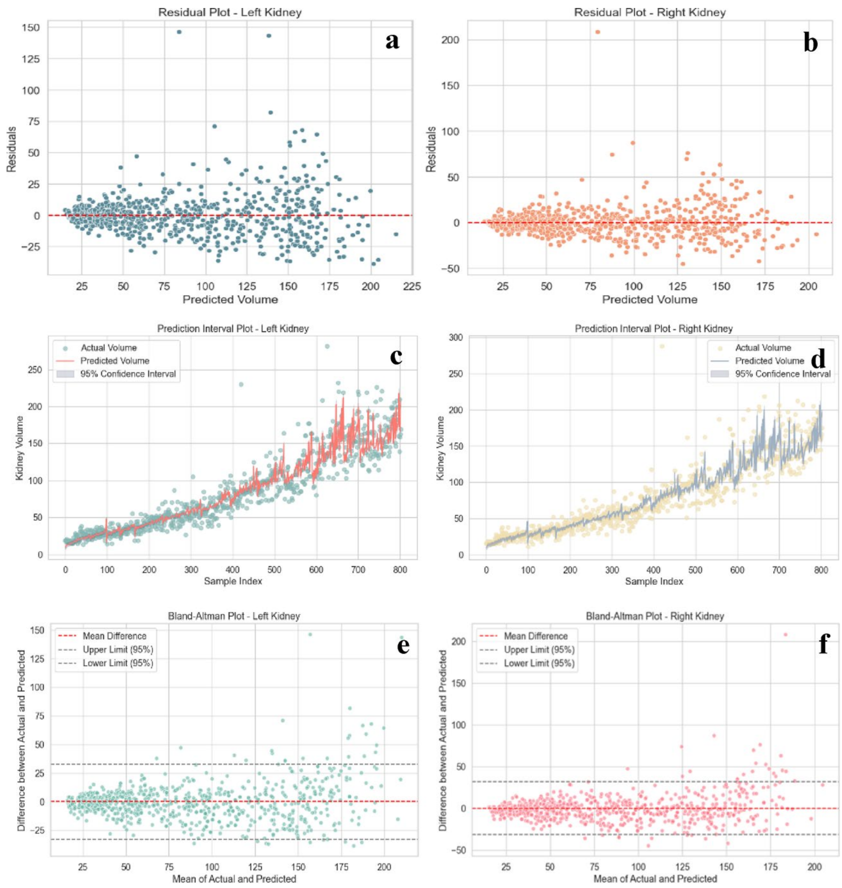

Fig. 3. Model accuracy visualization. (**a**–**b**): Residual plots assess the suitability and accuracy of the model by examining the random distribution of residuals around the horizontal red dashed line (y = 0), indicating good model fit if no apparent pattern is observed. (**c**–**d**): Prediction interval plots show the interval estimation of the predicted values, providing a visual assessment of model reliability by comparing actual values (scatter points), predicted values (curve), and the 95% confidence interval (gray area). The closer the actual values are to the predicted curve, the higher the prediction accuracy. Narrower confidence intervals indicate more precise model predictions. (**e**–**f**): Bland-Altman plots evaluate the differences and agreement between actual and predicted values, plotting the average of actual and predicted values (x-axis) against the difference (y-axis). The horizontal red dashed line represents the mean difference, and the gray dashed lines indicate the 95% limits of agreement. Most scatter points within these limits suggest good agreement between actual and predicted values.

using ellipsoid or other geometric formulas, which rely on kidney length, width, and anteroposterior diameter measurements[3,13]. However, these methods may not detect subtle changes in kidney volume and may suffer from accuracy and reproducibility issues. While 3D ultrasound can provide volume measurements, its results can be affected by operator subjectivity or patient positioning, especially in younger children prone to movement and may introduce artifacts. Additionally, 3D ultrasound measurements tend to underestimate actual kidney volume, which is consistent with our findings and other studies[1,14]. In contrast, CT and MRI offer greater accuracy and consistency in kidney volume measurement. Although MRI provides high-resolution imaging, it requires longer scan times and higher patient compliance. CT, however, offers high spatial resolution, reducing measurement errors and providing more precise kidney boundary delineation. Additionally, it is faster, making it more suitable for pediatric patients. In this study, we used the CAS system to process CT imaging data, which considers imaging parameters like pixel spacing and slice thickness. The system performs 3D reconstructions from axial, sagittal, and coronal views, allowing for accurate kidney volume measurements. Additionally, the CAS system can provide detailed information on the surrounding anatomical structures and the relationships with adjacent organs. It has been demonstrated to be compatible with various CT machines and DICOM files of differing slice thicknesses, further proving its accuracy and robustness in kidney volume measurement[15,16].

The differences in kidney volume between genders are still debated. Most studies show no significant differences in kidney volume between boys and girls[1,13,17]. Our study supports this finding, showing no significant difference across age groups. This suggests that renal development in childhood may be highly homogeneous regardless of gender. However, some studies report slightly smaller kidney volumes in girls, likely due to lower average body weight and surface area[18,19].

Our study also observed a significant difference between the left and right kidney volumes, consistent with previous literature that the left kidney is typically larger[20]. In our cohort, 79.08% of children had a larger left kidney, likely due to anatomical factors, as the right kidney's growth is constrained by the liver. Similar findings were reported by Shi et al., with a significant difference in average kidney volume between the left and right kidneys[1]. Interestingly, Schmidt et al. documented that the right kidney volume was slightly but significantly larger in both boys and girls ($p < 0.001$ and $p < 0.01$, respectively), making it the only study to find a larger right kidney[21]. These discrepancies suggest that kidney volume differences between the left and right kidneys may be influenced by genetic, developmental, and environmental factors.

Kidney volume correlates strongly with age, height, weight, and BSA, reflecting the unique characteristics of pediatric growth. In our study, BSA showed the strongest correlation with kidney volume (left kidney $r = 0.946$, right kidney $r = 0.943$), followed by weight (left kidney $r = 0.925$, right kidney $r = 0.923$). This high correlation can be explained by BSA being a more comprehensive measure of the body's overall size and metabolic capacity, as it accounts for both height and weight, factors that influence kidney development. BMI, on the other hand, showed the weakest correlation with kidney volume (left kidney $r = 0.519$, right kidney $r = 0.519$). This is likely because BMI, while reflecting body mass, does not directly account for other aspects of body composition, such as muscle mass and fat distribution, which could more strongly affect kidney size. These findings are consistent with the results from Obrycki et al. and Dinkel et al.[12,22]. However, Shi et al. reported that kidney volume correlates most strongly with age[1]. Our study is the first in China to provide reference ranges for pediatric kidney volume based on height and weight. We also found that kidney volumes across all age groups were larger than those reported in studies using 3D ultrasound, likely due to differences in measurement methods[1,14]. By dividing the measured kidney volume by BSA, we accounted for body size variations among individuals. We grouped the data by age and observed that kidney volume tends to increase with age, with the highest values seen in the 16–18 year age group, reflecting the final stages of renal development. Considering the body surface area of pediatric patients, these reference ranges can be used to assess kidney volume in clinical settings.

Changes in kidney volume often precede significant alterations in renal function. We developed simple regression equations for clinical use, based on height and weight as easily accessible data. The equations are as follows:

$$\text{Left kidney volume}: \ Y = -22.427 + 0.636 \times \text{Height} + 1.200 \times \text{Weight} \ \left(\text{cm}^3\right) \ \left(R^2 = 0.896;\ P < 0.01\right)$$

$$\text{Right kidney volume}: \ Y = -19.522 + 0.585 \times \text{Height} + 1.149 \times \text{Weight} \ \left(\text{cm}^3\right) \ \left(R^2 = 0.891;\ P < 0.01\right)$$

Residual plots and other visualizations indicate that these equations offer a high degree of accuracy and general applicability. Previous studies, such as those by Otiv et al., Fujita et al., and Duminda et al., focused on predicting kidney length using ultrasound, but these models are limited in assessing changes in kidney morphology and size comprehensively, as they do not account for kidney volume[23–25]. Additionally, Shi et al. used 3D ultrasound to measure kidney volume and developed prediction formulas, but their measurements tended to underestimate actual kidney volume[1,14]. In contrast, our models based on height and weight provide a more accurate and comprehensive prediction of kidney volume.

However, this study has several limitations. First, our study was limited to children and adolescents from the eastern coastal region of China, which may restrict the generalizability of our findings to other populations. While the results provide important reference values for the Chinese population, further studies are needed to assess their applicability to children from other regions and ethnic groups. Future research should include a larger sample size, incorporating children from diverse backgrounds to validate and adjust the reference values and predictive models for kidney volume. Additionally, this study did not collect information on factors such as kidney length and kidney function data, which will require prospective research. We are planning to conduct research on this aspect. Another limitation is the potential radiation risk posed to pediatric patients by the CT scans used in this study. Future research should consider including these variables and explore alternative, lower-radiation imaging methods, such as low-dose CT or MRI, to refine our models and predictive formulas.

Conclusion

In summary, this study provides reference values for kidney volumes in children and adolescents aged 0–18 years from the eastern coastal region of China and develops predictive formulas based on commonly available clinical data. These findings have significant clinical relevance as they can aid in early detection of renal developmental abnormalities, guide treatment decisions, and improve long-term renal health monitoring following nephrectomy. By applying these reference ranges and predictive models, clinicians can better assess kidney growth patterns and intervene early in cases of abnormal development. Future studies should expand the sample size and include more influencing factors to enhance the reliability and clinical applicability of the results.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

Y.L. contributed to data curation, formal analysis, methodology, visualization, and Writing—original draft . N.X. was responsible for data curation and formal analysis. X.Y. contributed to data analysis and visualization. F.W., F. W. contributed visualization. R.Z., Y.D., X.H. oversaw the project through supervision and review. X. C., C.B., N.X. contributed to reviewing, language editing, and supervision. Q.D. was responsible for conceptualization, funding acquisition, project administration, resource provision, and final review and editing. All authors approved the final version of the manuscript, with the first author ensuring that all authors have read and agreed to the manuscript's contents.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

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Additional information

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