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KIDNEYS, URETERS, BLADDER, RETROPERITONEUM

The influence of pelvicalyceal system anatomy on minimally invasive treatments of patients with renal calculi

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Abstract

Introduction and objectives Nephrolithiasis has a multifactorial etiology, wherein, besides metabolic factors, the anatomy of the pelvicalyceal system might play a role. Using 3D-reconstructions of CT-urography (CT-U), we studied the morphometric properties of pelvicalyceal anatomy affecting kidney stone formation and compared those with existing literature on their effect on minimally invasive treatment techniques for renal calculi.

Methods CT-U's were made between 01-01-2017 and 30-09-2018. Patients were chronologically included in two groups: a nephrolithiasis group when ≥ 1 calculus was present on the CT-U and a control group of patients with both the absence of calculi on the CT-U and no medical history of urolithiasis. Patients with a medical history of diseases leading to higher risks on urolithiasis were excluded. In the nephrolithiasis group affected kidneys were measured. In the control group, left and right kidneys were alternately measured.

Results Twenty kidneys were measured in both groups. Mean calyceopelvic tract width was significantly larger in the lower segments of affected kidneys (3.9 vs. 2.7 mm). No significant differences between the groups were found in number of calyces, infundibular length, infundibular width, calyceopelvic angle, upper–lower angle and diameters of the pelvis. Transversal calyceal orientation in hours was significantly smaller in the upper and lower segments of the nephrolithiasis group (7.69 vs. 8.52 and 8.08 vs. 9.09 h), corresponding with more dorsally located calyces in stone-forming kidneys.

Conclusion Pelvicalyceal anatomy differs between stone-forming and non-stone-forming kidneys. Understanding the pelvicalyceal system and etiology of stone formation can improve development of endourological techniques.

Keywords Nephrolithiasis · Anatomy · Pelvicalyceal system · Endourological treatment · Three-dimensional imaging

Introduction

Urolithiasis is a common disease in countries with a high standard of life, with a prevalence in Dutch general population of 5.5% [1]. The formation of renal stones has a multifactorial pathogenesis, wherein not only environmental, metabolic and dietary factors but also anatomical properties of the kidney play an important role [2–5]. Besides gross anatomical abnormalities, e.g. horseshoe kidneys, smaller-scale morphometric properties of the pelvicalyceal system are postulated to play a role in the pathogenesis of nephrolithiasis [6, 7]. Understanding these properties may influence improvement of minimally invasive surgical techniques for renal stones.

Starting in the early nineties, pelvicalyceal anatomy in correlation with urolithiasis has been described frequently [8]. Measurements on the lower pole renal infundibulum were used as primary outcome in many previous studies. Most of these studies have been performed using two-dimensional (2D) intravenous urographys (IVU), with the aim to investigate the influence of pelvicalyceal anatomy on success and complication rates of nephrolithiasis treatments [9]. In contrast to the 2D IVUs, modern radiological techniques enable measurements in three-dimensional (3D) planes. When compared to traditional methods, 3D-visualization techniques are more effective in improving understanding of anatomy [10]. Furthermore, performing measurements on 3D computed tomography urography images (CT-U) could lead to higher accuracy of those measurements when compared to IVUs [11]. Additionally, the possibility of using

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transversal images has led to the development of new measurement techniques, that could not be performed on anteroposterior IVUs [12].

As mentioned before, the most frequent reason to study renal anatomy is because the outcome of an endourological treatment is influenced by the morphometric properties of the pelvicalyceal system [13, 14]. With improvement of technology in endourology such as digital flexible ureterorenoscopes (fURS) and percutaneous nephrolithotomy (PCNL), success rates of stone treatment have increased and operating time has decreased [15, 16]. Still, a limitation of the current generation of flexible ureteroscopes is their disability to reach difficult places due to the anatomy of the kidney such as (the anterior/dorsal calyx of) the lower pole, as a result of the relatively limited bending mechanism of the fURS. If certain morphometric properties of the pelvicalyceal system would both amplify kidney stone formation and impede intrarenal treatment success, a difficulty for the endourologist is imposed.

In our recent manuscript, we reported a technique to quantitatively describe the pelvicalyceal anatomy [12]. Now, we question which morphometric properties of pelvicalyceal anatomy lead to a higher risk of kidney stone formation. Moreover, we studied if those correspond with the morphometric properties described in the literature as making areas of the kidney harder to reach in intrarenal surgery. In this manuscript, we compare pelvicalyceal anatomy between stone-forming and non-stone-forming kidneys. Using multiplanar reconstruction of CT urography, we performed a broad span of measurements on upper, interpolar and lower segments of 20 stone-forming and control kidneys.

Methods

A list of all CT-U made in Haga Teaching Hospital between 01-01-2017 and 30-09-2018 was obtained from the radiology department. Patients were divided into two groups: a nephrolithiasis and a control group. In both groups only adult patients (age ≥ 18 years) were included. For inclusion in the nephrolithiasis group, at least one nonobstructive calculus ≥ 3 mm had to be present in the ureter or pelvicalyceal system on the CT-U. Calculi causing hydronephrosis were not included. A CT-U without nephrolithiasis was only assigned to the control group when the patient did not have urolithiasis in his previous medical history. Indication for CT-U was either hematuria or suspicion of urolithiasis. Measurements were performed on one kidney per patient. For the nephrolithiasis group, only the affected kidney was used. For the control group left and right kidneys were alternately used. Exclusion criteria were evident urological pathology on the CT-U (including hydronephrosis and congenital malformations) and previous surgery of the urogenital tract. Furthermore, patients with a medical history of diseases associated with an enlarged risk of nephrolithiasis as described in the latest EAU-guideline were excluded, including patients with metabolic disorders causing stone formation [17]. The radiology reports and patient records were checked for eligibility for inclusion in the nephrolithiasis or control group.

Patient data such as age, length, weight, body mass index (BMI) and medical history were obtained from patients' electronical medical record. 3D-reconstructions of late phase scans of CT-U (+ 10 min) were used for all measurements, made by the multiplanar reconstruction and maximum intensity projection functions of Phillips Intellispace Clinical Applications 8.2©.

Based on the configuration of the pelvicalyceal system, the kidneys were split into upper, interpolar and lower segments. The number of calyces was counted per segment. For the nephrolithiasis group locations and largest diameter of calculi ≥ 3 mm was noted. For each calyx infundibular length (IL), calyceopelvic angle (CPA), infundibular width (IW), calyceopelvic tract width (CPTW) and transversal calyceal orientation (TCO) were measured. IL was measured as a straight line between the infundibulopelvic junction and the most distal point of the corresponding calyx. CPA was measured as the inner angle of the intersection of the ureteropelvic axis and calyceal axes. Ureteropelvic axis links the center of the ureter at the level of the lower pole to the center of the pelvis. IW was measured as the smallest point on the infundibular axis. CPTW was measured as the smallest point of the tract from each calyx to the pelvis. Measurements of IW and IL were performed as described by Elbahnasy. CPA and CPTW were derived from IW and infundibulopelvic angle (IPA) as described by Elbahnasy [9]. TCO was measured based on a clock system, as described in our recent publication [12]. Renal hilum was positioned on three o'clock. Measurements were performed clockwise for right and counterclockwise for left kidneys. Consequently, nine, twelve and six o'clock positions represented lateral, anterior and posterior positions, respectively. See Fig. 1 for additional illustrations. Furthermore, craniocaudal, mediolateral and anteroposterior diameters of the renal pelvis were measured. Upper lower calyceal angle (ULA) was measured as the angle between the axes of the two upper and lower calyces.

Data were analyzed with SPSS 25.00 (IBM corp. 2017). Numerical data were, if normally distributed, noted as mean (standard deviation) and analyzed using independent samples *t* tests. IL, CPA, IW, CPTW and TCO were analyzed separately for upper, interpolar and lower segments. Linear mixed models were used to analyze these repeated measurements. χ^2 tests were used to analyze categorical data. p values < 0.05 were considered statistically significant.

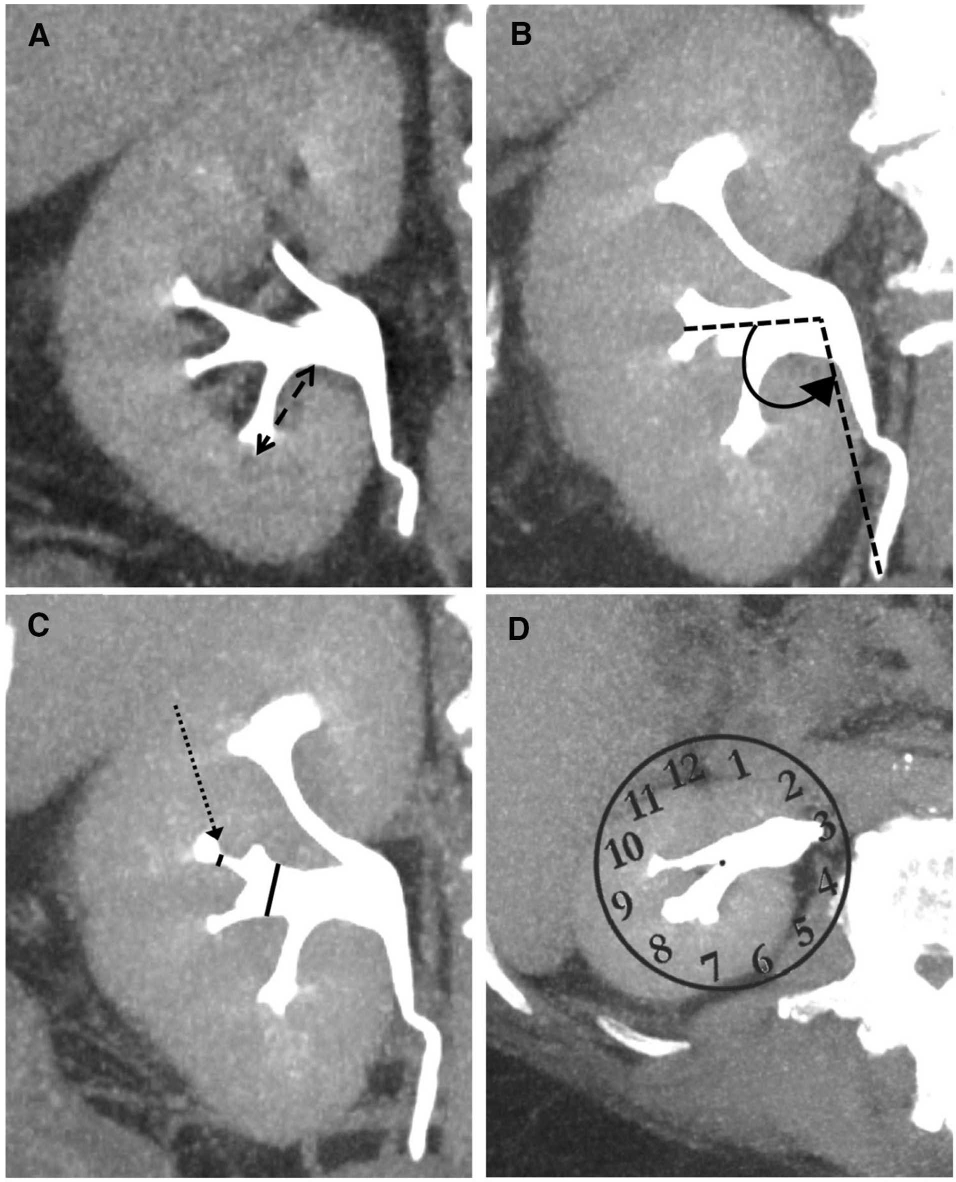

Fig. 1 Illustration of the measurements on pelvicalyceal anatomy. Panel **A** shows IL as measured for a lower pole calyx, panel **B** shows CPA as measured for an interpolar calyx, panel **C** shows IW and CPTW (marked with arrow) as measured for an interpolar calyx and panel **D** shows TCO as measured using the clock system

Results

A total of 350 patients were checked for eligibility for inclusion. A total of 188 (53.7%) patients were excluded, based on the radiology report ($n=138$, 73.4%), medical history ($n=37$, 19.7%) and inappropriate quality of the imaging ($n=13$, 6.9%). Of the remaining 162 patients eligible for inclusion, twenty were eligible for the nephrolithiasis and 142 for the control group. Chronologically, based on date of the CT-U, twenty patients were included in both groups, starting with the first eligible CT-U made in 2017. Table 1 illustrates the characteristics of the nephrolithiasis and the control group.

Average age of the patients was 58.1 and 64.9 years for the nephrolithiasis and control group, respectively. In the

Table 1 Patient characteristics per group

	Nephrolithiasis group $N=20$	Control group $N=20$	p value
Gender (male)	15 (75.0%)	12 (60.0%)	0.311*
Measured kidney side (left)	12 (60.0%)	10 (50.0%)	0.525*
Age (years)	58.1 (14.9)	64.9 (15.0)	0.158†
Length (m)	1.75 (0.06)	1.71 (0.12)	0.329†
BMI (kg/m^2)	26.6 (5.1)	27.7 (5.6)	0.593†

Data is described as number (%) or mean (standard deviation). Data was analyzed with: *Pearson χ^2 test and † independent t test nephrolithiasis group 75.0% ($n = 15$) of patients was male and in the control group 60.0% ($n = 12$). Average length and BMI did not differ significantly between both groups. Left kidneys were measured in 12 patients (60.0%) of the nephrolithiasis group and in 10 patients (50.0%) of the control group. For the nephrolithiasis group, most of the calculi were located within the kidney ($n = 16$, 80.0%), of which three (15.0%), six (30.0%) and seven (35.0%) were in the upper, interpolar and lower segment, respectively. Remaining patients had a calculus located in the ureter ($n = 2$, 10.0%) or pelvis ($n = 2$, 10.0%). All patients in the nephrolithiasis group had one calculus ≥ 3 mm ($n = 20$, 100%). Median diameter of calculi was 5.2 mm (3.0–13.2).

Table 2 shows the outcomes of morphometric measurements for both groups. Median numbers of calyces did not significantly differ between the nephrolithiasis group and the control group (7.5 vs. 9.0 calyces, $p = 0.28$). In addition, when the total of calyces was split per segment, no significant differences were found.

In all three segments, no significant difference in IL was found between both groups. IW was larger in the nephrolithiasis group in all three segments, but did not differ significantly from the control group. CPTW was larger in the nephrolithiasis group in all three segments as well, with a significantly larger mean lower segment CPTW in the nephrolithiasis group (3.9 vs. 2.7 mm, $p = 0.039$). Mean CPA was bigger in the upper and interpolar segments compared to the lower segment, but no significant differences between the groups were found.

Mean TCO in hours was smaller in the nephrolithiasis group in all three segments, compared to the control group. Upper segment TCO (7.69 vs. 8.52 h) and lower segment TCO (8.08 vs. 9.09 h) were significantly smaller in the nephrolithiasis group ($p = 0.045$ and $p = 0.030$). This corresponds to significantly more dorsally located calyces in the nephrolithiasis group, compared to relatively more laterally located calyces in the control group.

Diameters of the pelvis did not significantly differ between both groups, with mean craniocaudal diameters of 19.8 and 13.5 mm ($p = 0.052$), mean mediolateral diameters of 19.8 and 18.1 mm ($p = 0.27$) and mean anteroposterior diameters of 9.8 and 8.3 mm ($p = 0.17$) for the

Table 2 Measurements of pelvicalyceal anatomy compared between groups

	Nephrolithiasis group	Control group	*p*-value
Total kidney calyces (*n*)	9.0 (5–15)	7.5 (5–20)	0.277*
Upper segment calyces (*n*)	3.0 (1–8)	3.0 (1–7)	0.968*
Interpolar segment calyces (*n*)	3.0 (1–5)	2.5 (0–6)	0.678*
Lower segment calyces (*n*)	3.0 (2–4)	3.0 (1–7)	0.398*
Upper segment IL (mm)	27.1 (7.8)	29.3 (10.1)	0.478†
Interpolar segment IL (mm)	19.3 (6.7)	17.8 (7.6)	0.361†
Lower segment IL (mm)	25.1 (6.7)	25.2 (7.5)	0.838†
Upper segment IW (mm)	4.1 (1.9)	3.8 (1.9)	0.390†
Interpolar segment IW (mm)	3.0 (1.8)	2.3 (1.6)	0.236†
Lower segment IW (mm)	5.5 (1.8)	4.4 (2.3)	0.105†
Upper segment CPTW (mm)	3.4 (1.5)	2.8 (1.7)	0.182†
Interpolar segment CPTW (mm)	2.5 (1.5)	2.3 (1.6)	0.768†
Lower segment CPTW (mm)	3.9 (1.8)	2.7 (1.7)	0.039†
Upper segment CPA (°)	115.7 (34.1)	116.3 (35.4)	0.888†
Interpolar segment CPA (°)	115.4 (26.1)	114.1 (28.9)	0.710†
Lower segment CPA (°)	70.8 (37.5)	73.3 (41.1)	0.092†
Upper segment TCO (hrs)	7.69 (2.24)	8.52 (2.07)	0.045†
Interpolar segment TCO (hrs)	9.25 (1.25)	9.42 (2.30)	0.657†
Lower segment TCO (hrs)	8.08 (2.44)	9.09 (1.65)	0.030†
ULA (°)	191.0 (57.1)	201.7 (58.5)	0.562†
CC diameter pelvis (mm)	16.9 (6.6)	13.5 (3.9)	0.052†
ML diameter pelvis (mm)	19.8 (4.7)	18.1 (5.0)	0.271†
AP diameter pelvis (mm)	9.8 (3.6)	8.3 (3.1)	0.166†

Number of calyces (total kidney and per segment) is described as median (range), the other outcomes are described as mean (standard deviation). Data was analyzed with: *Mann–Whitney U test and †mixed linear models

IL infundibular length, *IW* infundibular width, *CPTW* calyceopelvic tract width, *CPA* calyceopelvic angle, *TCO* transversal calyceal orientation, *ULA* upper–lower calyceal angle, *CC* craniocaudal, *ML* mediolateral, *AP* anteroposterior nephrolithiasis and control group, respectively. Mean ULA was 191.0° for the nephrolithiasis group and did not differ significantly from the control group (201.7°, $p=0.562$).

Discussion

Although metabolic factors have proven to play an important role in the etiology of urolithiasis, current knowledge on this subject is inconclusive to explain the complete process of kidney stone formation. In this manuscript, our main goal is to investigate the role of pelvicalyceal anatomy in the formation of renal calculi by performing morphometric measurements on both stone-forming and control kidneys using 3D reconstructions of CT-U. We found significantly more dorsally located calyces in both upper and lower segments and a significantly wider CPTW in lower segments of stone-forming kidneys.

We postulate that if a role of pelvicalyceal anatomy in stone formation was to be found, the complete tract from calyx, where the renal papillae empty their urine, to pelvis had to be investigated. Common opinion is that stone formation initiates within the renal papillae, either by stone formation on Randall's plaques, plugging of Bellini's ducts or by free solution stone formation [18]. Starting in the calyx, the urinary flow-pattern might be influenced by the width and length of the tract and the sharpness of the corners in this tract. As this tract is different for each calyx, we decided, enabled by modern imaging and software techniques, to individualize measurements for each calyx. In addition to IW, we measured CPTW as the narrowest point from calyx to pelvis and, in contrast to most previous studies, we measured CPA instead of IPA. The CPA was derived from IPA as described by Elbahnasy; the individualized calyceal axis is used instead of the infundibular axis, while the same ureteropelvic axis is used [9].

Few studies have been published with focus on the correlation between pelvicalyceal anatomy and the etiology of stone formation. Kupeli et al. performed measurements of pelvicalyceal anatomy in all three segments of lower pole stone-bearing kidneys and contralateral kidneys, using 2D IVU's. Their main findings were a smaller interpolar IPA, larger upper IL and larger upper and lower IW [7]. Thus, even though calculi were only present in lower poles of kidneys, they found significant differences in the upper and interpolar segments, leading to the conclusion that stone formation does not depend solely on the lower pole pelvicalyceal anatomy. Stones can migrate over time and this could be a possible explanation for Kupeli's finding of significant differences in upper and interpolar segment anatomy: some of the lower pole calculi included by Kupeli might have originated from upper or interpolar segments and migrated to the lower segment. We likewise found a significant correlation between kidney stone formation and both upper and lower segment anatomy.

We found a trend of larger IW's and CPTW's in the nephrolithiasis group, with significantly larger CPTW in lower segments of stone-forming kidneys. Likewise, both Kupeli and Gökalp et al. found significant larger IW in the stone-forming kidneys [6, 7]. Gökalp et al. measured lower pole pelvicalyceal anatomy on IVU and compared 119 kidneys with a unilateral single lower pole calculus with 80 kidneys from 40 random control patients. Gökalp found a significantly larger lower infundibulum diameter (corresponding with IW) and longer inferior calyceal length in stone-forming kidneys. They measured inferior calyceal length from the most distal point of a calyx to the medial side of the pelvis opposing the infundibulum. Consequently, a larger pelvis would as well lead to a larger inferior calyceal length. We individually measured IL and the mediolateral diameter of the pelvis and found no significant correlation with stone formation.

Similar to our study, Balawender et al. used CT-U for performing measurements on lower pole pelvicalyceal anatomy. They compared lower pole anatomy of 75 kidneys with a single lower pole calculus with the contralateral kidney. Of all measured outcomes, Balawender found only a significantly smaller IPA as described by Sampaio in the stone-bearing kidneys. We compared CPA instead of IPA and found no difference between the groups.

A possible explanation of our finding of more dorsally located calyces in stone-forming kidneys could be an increased stasis of urine in those calyces, due to gravitational effects during sleeping in a supine position. As measurements on the pelvicalyceal anatomy in the transversal plane have only become possible after the development of the multiplanar CT's, very limited number of comparable studies have been performed with measurements on the transversal plane as outcomes. Sanal et al. compared transversal rotation of stone-forming and contralateral kidneys by measuring the angles between the renal pelvic line and median sagittal line of the vertebrae on unenhanced CT-scans. They found that stone-forming kidneys have a more anteriorly faced pelvis [19]. Our results show that the average calyx is located nearly opposite to the renal hilum. Thus, a more anteriorly faced renal hilum corresponds with more dorsally located calyces in stone-forming kidneys, making their finding complementary to ours.

Furthermore, a meta-analysis on the role of pyelocaliceal anatomy in the outcomes of retrograde intrarenal surgery was recently published by Karim et al. Their meta-analysis showed no significant differences in IPA, IL and IW between kidneys with successful and unsuccessful procedures [20]. Although we did find a trend of larger IW and significantly larger lower CPTW in stone-forming kidneys, ureterorenoscopic treatment success is not influenced by it. All studies reviewed in Karim's manuscript performed measurements on 2D IVU's or retrograde pyelographies. Consequently, no measurements in the transversal plane were performed in those studies. In retrograde intrarenal surgery, the pelvicalyceal system is entered at the ureteropelvic junction at the renal hilum. Calyces located straight opposite to the hilum, corresponding with a TCO at 9 o'clock, require minimal turning of the scope for accessing the calyx, though flexing of the scope is frequently necessary because of the IPA. We found that in stone-forming kidneys the mean upper and lower calyx was orientated further away from the 9 o'clock point. Thus, these calyces require a sharper turn that has to be made for accessing the calyx. One could imagine that an increased sharpness of the turn would influence the difficulty of accessing areas of the pelvicalyceal system, thereby impeding treatment success rates, though no studies have objectively investigated this. Furthermore, calyces with both a dorsomedial orientation and a small IPA would require sharp turning as well as extensive flexing of the ureterorenoscopes. In the future, an ureterorenoscope with the ability to flex in two planes could prove to be a better solution for such calyces and might improve treatments success rates. Further research using individualized measurements on the stone-bearing calyx, including measurements on the transversal plane, is advised to improve prediction of success rates of intra renal surgery.

One of the limitations of this study is that control kidneys came from different patients than the stone-forming kidneys. Even though we found no significant differences between both groups in age, length, BMI and side of kidney measured, differences in metabolic states between both groups could be present. Moreover, morphometric properties of the pelvicalyceal system were measured at one point in time. These static measurements do not take possible dynamics of pelvicalyceal system anatomy into account. Furthermore, as only part of the included patients had calculi located in calyces and migration between calyces could have occurred, no conclusions could be drawn for individual calyces and no correlation between calculus location and pelvicalyceal anatomy was studied. Finally, we performed a retrospective study on a limited number of kidneys. Prospective research on a larger number of kidneys could further improve accuracy of results.

In conclusion, pelvicalyceal anatomy differs when comparing stone-forming kidneys with a non-stone-forming control group. While we did find significant differences in anatomy in more than just the lower segment, none of our outcomes showed significant correlations in all of the three segments. These differences could have implications in minimally invasive treatment of renal calculi. Understanding the pelvicalyceal system and etiology of stone formation can improve development of endourological treatment techniques.

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