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Studies on the Influence of the Flow Field in the Pelvi-Calyceal System (PCS) on the Formation of Urinary Calculi

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Summary. Following a morphological analysis of pelvi-calyceal systems (PCS) of healthy persons and urolithiasis patients, rheological studies from glass and rubber PCS-models are presented. In the PCS of urolithiasis patients morphological and geometrical differences were found, causing a flow pattern which favours calculus formation. In urolithiasis, the PCS is characterized by cavities with significantly reduced flow rates and stagnation of urine. The formation of urinary calculi is often promoted by a hypomotility of the muscles of the PCS, common in urolithiasis patients. Possible therapeutic and diagnostic consequences are discussed.

Key words: Formation of urinary calculi, Fluid dynamics, Morphology of the renal pelvis.

Introduction

Urinary calculi are the products of biomineralization in the urinary systems.

Following supersaturation of urine with calculus forming salts a nuleus (homogeneous or mainly heterogeneous) develops.

Crystalluria may be regarded as physiological as long as the crystals formed in the urinary tract are excreted in the urine.

Subsequent growth, by the aggregation of nuclei, however, must be regarded as pathological, i.e. processes in which the crystal aggregations reach dimensions which prevent them from leaving the PCS and result in a urinary calculus.

The formation of urinary calculi is promoted when the concentration of inhibitors of nucleus formation, growth and aggregation is insufficient.

Although these conditions exist in many patients, no calculus is formed. Therefore at least one more precondition must exist before a urinary calculus is formed.

Flow in the PCS might influence calculogenesis, as presented in this study. Crystals and crystal aggregations must remain in the PCS for a certain period of time to allow growth [20]. A prolonged stay of particles in the PCS, spaces with low flow rates or a (re-)circulating flow infers "whirlpools".

Apart from this "free" formation, the fixation of particles in the PCS must also be included in consideration of this problem [16].

Free growth in a (re-)circulating flow results in an attachment of materials from all sides so that, starting from the centre of growth, annual-ring-like structures can be observed on polished, or thin sections of, urinary calculi.

However, our studies have shown that most calculi have several centres of growth whose structure shows that they must have grown on an area of the PCS wall with disturbed epithelia before aggregation [1, 15, 24, 25].

Randall plaques may also be regarded as "fixed particles", though not on the basis of primary fixation but rather as an interstitial calcification [10, 13]. The intact mucous lining of the PCS prevents adhesion of any foreign body [3].

The hypotheses that flow patterns within the collecting system influences duration of stay of crystal aggregations and particles is supported by a number of other findings. These include morphological comparisons and motility studies on PCS of healthy persons and of urolithiasis patients [4, 9, 14, 15, 17, 18, 23].

The interpretation of these contradictory statements is difficult. The primary urine formed in Bowman's capsule flows into the calyces minores (Fig. 1). According to Lullies and Trincker [11], this is caused by a pressure difference of 2.0 ... 2.7 kPa but according to Düx et al. [5] it is a passive process. Distally the calyces minores are closed by Henle's sphincters. They open at a certain filling pressure. At the same time, the corresponding sphincter of Disse ought to close so that the calyces majores, are filled [2, 5]. Above a filling pressure which causes a stretch stimulus to the geometry of the muscle cells, the respective calyx majoris contracts the corresponding sphincter of Henle closes, and the

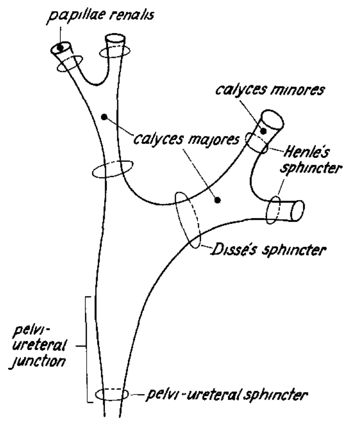

Fig. 1. Scheme of muscle groups in the PCS which are of importance for urinary transport

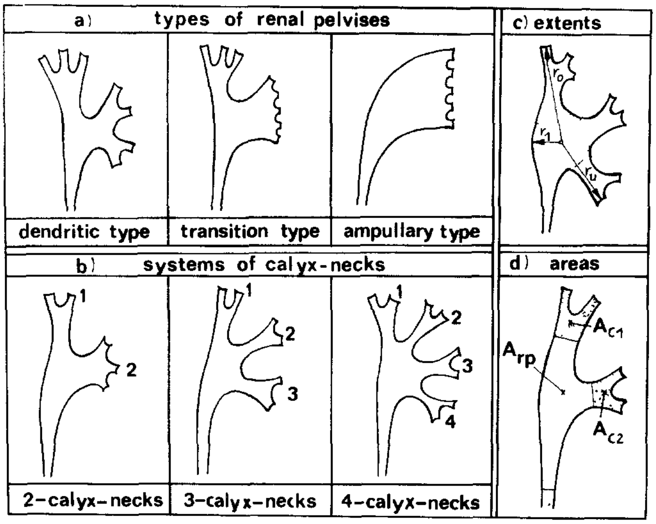

Fig. 2a–d. Types of renal pelvis (a). b classification of PCS according to the number of calyceal-necks opening into the renal pelvis. c extent of the typical radii r_1, r_0 and r_u which characterize the PCS. d proportions of the PCS (area)

sphincter of Disse opens. Thus a Bolus of urine is propelled into the renal pelvis.

The outlet of the renal pelvis can be closed by the pyelo-ureteral sphincter. The pyelo-ureteral junction (PUJ) is of special importance as a pacemaker [5, 9, 14].

After onset of an initial contraction at the conus ureteralis (Fig. 1), apparently due to stretch stimulus and diuresis, and hence to the filling pressure at the outlet of the renal pelvis, a urine Bolus travels by peristalsis from the renal pelvis via the ureter into the bladder. Recent investigations, e.g. of Hannappel [8], have demonstrated that the smooth muscles of the PCS may be regarded as a functional syncyticum. In addition to the "classical" pacemaker at the PUJ, other primary pacemakers with a higher base frequency exist in the more intrarenally situated portions of the renal pelvis. The transport system is adapted to variations in diuresis by blocking the myogenic conduction. The sucession of calyceal contractions, their coordination with pelvic contractions as well as the completeness of occlusion in the sphincter of Disse and Henle are still poorly understood.

The problem was to determine flow fields in the PCS of healthy persons and of urolithiasis patients, and having accounted for volume flow, and the type of the renal pelvis, we assessed the influence of flow pathways in the PCS on the formation of urinary concrements.

Methods

Even with the latest diagnostic display methods (X-ray videography, computerized tomography, magnetic resonance tomography) it is not possible to measure and analyze flow fields in the human PCS. Neither is it possible to describe the existing flow system in a purely mathematical manner as several essential factors are still unknown.

A replica of the PCS in a physical model, offers an advantageous method of investigation. Floris and Riga [7], Marberger [12], and Zechner and Lobenstein [27] have reported flow studies on bent glass pipes or models resembling the renal pelvis. In these studies, the experimental models were not sufficiently analogous to the human situation to allow conclusions to be drawn.

Morphological studies were made from infusion urograms and polyacrylate casts of kidneys from cadavers. A total of 242 healthy kidneys and 104 PCS from stone patients were studied [15, 17].

First simple static glass models were obtained, and from these transparent rubber models of the PCS were developed for the flow experiments. In these experiments the urodynamic transport process was imitated by mechanical closing devices. The flow pattern could be traced by floating particles [15, 20]. It is important to observe certain rules of similarity which guarantee physical and geometrical similarity of the models. Dimension analysis resulted in six indices of similarity, which must be measured on the original system and adjusted and maintained on the model by adequate experimental conditions (fluid, temperature, volume flow ...).

The technical production of the models as well as the performance of the experiments have been described in detail [15, 20, 21, 22], and the mathematical analysis were described by Weber [26].

Results

Morphological Differences Between PCS of Healthy Persons and Urolithiasis Patients

Of a total of 346 PCS patterns, 85 parameters were registered per PCS, e.g. type of renal pelvis, geometrical data: dimensions, angles, areas, volumes as well as the degree of order, ramification and the number of branches in the calyceal groups, for details [5, 11].

The following statistically established differences are characteristic of the PCS of urolithiasis patients:

- 30% fewer dentritic types of renal pelvis (Fig. 2a)
- 31% more transition types of renal pelvis (Fig. 2a)
- 17% fewer two-calyx-neck systems (Fig. 2b)
- 15% more three-calyx-neck systems (Fig. 2b)
- on an average 2.6 more papillae
- larger extrarenal extent of the calyx groups from a fixed centre in the renal pelvis (average between 4 and 4.6 mm) (Fig. 2c)

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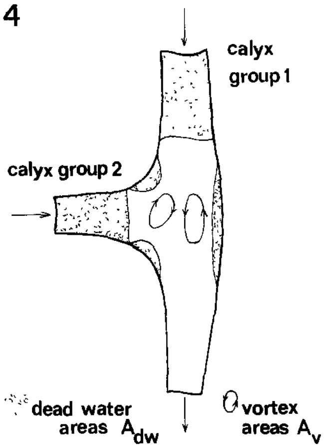

Fig. 3. Long-term photograph of a selected flow process in a glass model of the renal pelvis (model for demonstration)

Fig. 4. Dead water A_{dw} and vortex areas A_v which can be planimetrically determined from long-term photographs

- larger areas of renal pelvis or calyx in the urogram (Fig. 2d)
- correspondingly larger homologous volumes
- larger calyx-neck diameters (average up to 3 mm!)
- about 10% more high insertions of ureter to pelvis
- a higher degree of order reflected by a higher degree of calyceal-group ramifications (up to two additional ramifications on average) and by a higher number of branches in the calyx-groups (two to three additional branches on average).

Strangely enough, the majority of angles between the calyx necks and between calyx necks and renal pelvis were not different from those in healthy persons.

Assuming equal volumes of daily excretion for healthy persons and urolithiasis patients, the differences lead to the following hypotheses: because of their

- larger dimensions and
- higher ramification,

PCS of urolithiasis patients are characterized by

- less frequent contractions (due to bigger volumes)
- prolonged filling periods, particularly with regard to the calyx groups (volumes of calyx groups may even be doubled)
- lower flow rates of urine (due to a higher degree of ramification and larger cross sections)
- greater decrease of pressure (due to larger extent and ramification of the tube system)
- larger areas with very low flow rates (due to a lower proportion of dendritic PCS).

Thus the "unfavourable" PCS types might be predisposed for concrement formation as a result of morphological differences and certain physico-chemical properties of the urine. The calyx groups, and especially those situated proximally, are particularly at risk.

Results of Studies on Renal Pelvis Models of Glass

From long-term photographs (see Fig. 3 as an example for demonstration), the dead water and vortex areas A_{dw} and A_v, respectively (Fig. 4) could be measured planimetrically depending on volume flow (flow/time).

These areas are correlated with the corresponding homologous volumes [19].

The influence of the third position coordinate was neclected as it proved to be unessential [21]. In Fig. 5 the result of this determination of areas are plotted against on volume flow Q_M (index M: model) and Reynold's number Re.

These calculations suggest that

- There are great variations in the flow fields of the pelvicalyceal system.
- Under the same experimental conditions, PCS from urolithiasis patients show larger vortex and "dead-water-like" zones.
- Increasing volume flow Q_M as a rule results in smaller vortex and larger dead zones.
- Laminar flow is observed as a result of small Reynold's numbers.

These results obtained on glass models of renal pelvis must not be overestimated because the actual course of contraction as already described cannot be imitated. The statements, however, indicate trends and are true for the flow condition at the moment of renal pelvis systole with an open PUJ.

It is also of importance that particularly large dead water areas result when only some calyx groups are functionning, i.e. if urine flows only from one calyx majoris into the renal pelvis, see Fig. 2. Of special importance is the upper calyx group which may exhibit reduced motility or may not work at all.

Results of Studies on Renal Pelvis Models or Rubber

In these experiments the pyelo-ureteral sphincter was imitated by a closing mechanism. The pressure in the renal pelvis could be measured by means of a pressure transducer, and a control mechanism opened the artificial "pyelo-ureteral sphincter" at a preset opening pressure p_{max}. For detailed description of the experiment [22]. All experiments show a typical pressure-time course (Fig. 6):

- an expulsion period A,
- a closing period V and
- a filling period F.

Image analysis of the narrow-gauge film produced from the flow experiments, i.e. temporal and local tracing of the marked particles, revealed laminar flow in the filling and expulsion periods. The closing period plays a special role. Here an irregular back flow can be observed "whirling up" the contents of the renal pelvis. The extent of the back

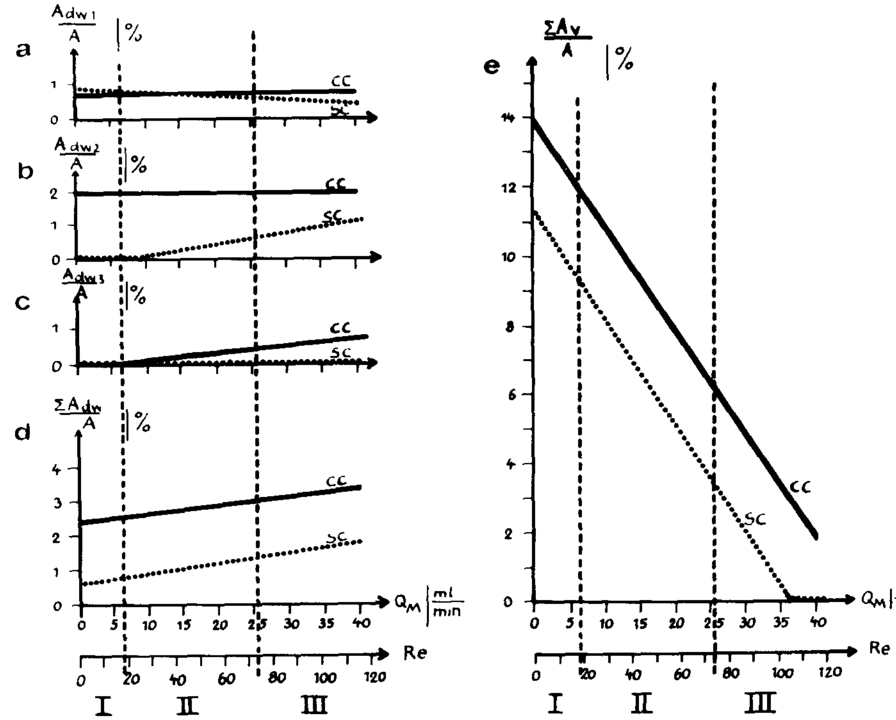

Fig. 5. Dependence of the proportions of dead water zones A_{dw}/A and of vortex areas A_V/A on the flow Q_M, with A being the total area. Abbreviations and symbols: *cc*, with calculus; *sc*, without calculus; *I*, oliguria; *II*, normal diuresis; *III*, polyuria

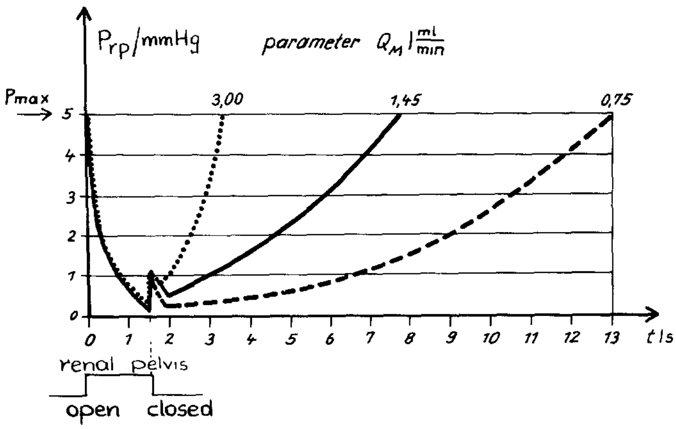

Fig. 6. Pressure/time course of a complete contraction cycle of the PCS

flow is largely dependent on the damping of the closing force, i.e. on the visco-elastic properties of the muscles. Vortex areas can only exist for short periods and break down constantly because of intermittent contractions. From the film the pathways of the marked particles and thus the distribution of flow rates in the PCS can be determined. This results in isotach fields, i.e. lines with the same flow rate dependant upon the time of observation. Figure 7 shows an example. If the distribution of flow rates is known, it is possible to calculate forces acting on particles fixed to the wall of the PCS. Primarily these are bending tensions which are about ten times higher than tension caused by linear forces which are also present. The bending tensions σ_b are dependent on the squared flow rate $\sigma_b = f(v^2)$, with v being flow velocity. Figure 8, e.g., shows the effective bending tensions (here as normed amount q) on

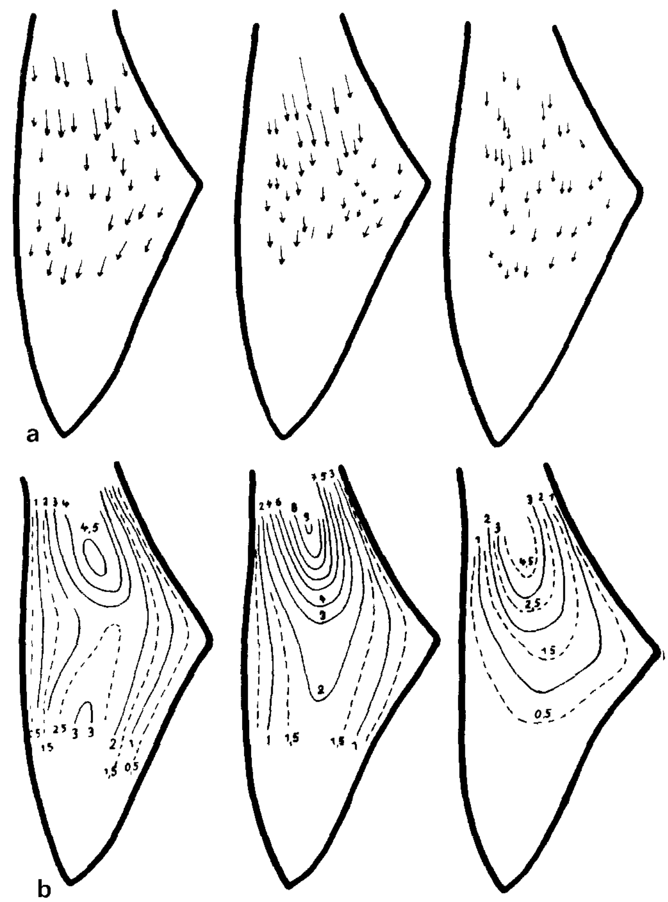

Fig. 7a, b. Flow pathways (a) and isotach fields (b) of a selected experimental example, the figures at the isotachs stand for flow velocity $v/\frac{mm}{s}$

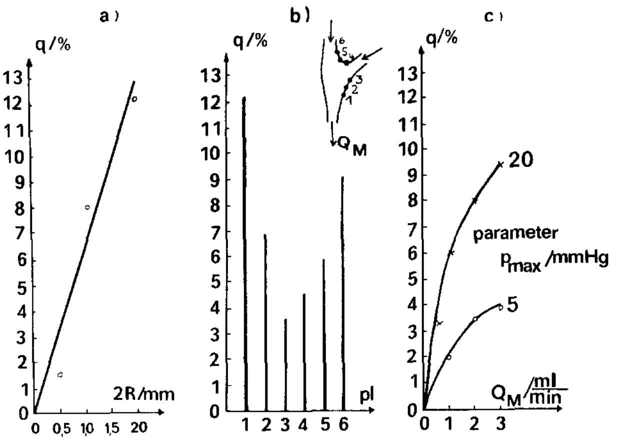

Fig. 8a–c. Dependence of the effect of force on fixed particles on the PCS wall; here as bending tension q as a function of a particle diameter 2R; **b** place pl of determination in the PCS and; c volume flow Q_M with the parameter pressure of maximal filling p_{max}

Table 1. Duration of stay Δt_d or Δt_d^x of the urine in the PCS in dependence on volume flow Q_M and maximal filling pressure p_{max}.
Δt_d. duration of stay measured in experiments with washing out dyes
Δt_d^x: duration of stay calculated by dividing V_{rp}/Q_M with V_{rp} = 1.1 ml (volume of filled renal pelvis model)

Q_M $\frac{ml}{min}$	a) Δt_d/s				b) Δt_d^x/s
	p_{max}/mmHg				
	5	10	15	20	
0.375	472	477	444	378	176
0.750	304	295	279	232	88
1.450	147	147	144	102	46
3.000	70	65	59	46	22
6.000	30	25	25	21	11

the particle size (Fig. 8a), place in the renal pelvis (Fig. 8b) and volume flow Q_M and maximal filling pressure p_{max} (Fig. 8c).

The time spent by the particles in the PCS is a parameter of decisive importance for calculus growth and formation of aggregations.

If renal pelvis models of rubber are used it is relatively easy to mark the filling of the renal pelvis with dye solutions. The duration of stay Δt_d can either be measured directly during the subsequent washing-out of the dye, or it can be calculated according to

$$\Delta t_d = n_c \cdot \Delta t_c \qquad \text{(i)}$$

with n_c being the number of cycles required to wash the dye out completely and Δt_c the time of one cycle.

Table 1a presents the measurement results related to volume flow Q_M and maximal filling pressure. The data are mean values, from each of 10 experiments. Standard deviations are not given for reasons of clarity.

Starting from the calculation

$$\Delta t_d^x = V_{rp}/Q_M \qquad \text{(ii)}$$

for the duration of stay. Finlayson and Reid [6], the results given in Table 1b are obtained for the rubber pelvis used here with V_{rp} = 1.1 ml.

But there is no complete exchange of volumes as must be assumed using formula (ii), but in the PCS mixed zones must be taken into consideration which increase the actual duration of stay. In our case this results in an increase by a factor of approximately 3. It must be pointed out that the difference may be much higher with bigger renal pelvis volumes.

Discussion

Model technology has proved to be a satisfactory method of analysis of flow in the PCS.

The present results reflect the importance of the flow field in the PCS which determined the retention of crystals and aggregations which formed free or fixed.

According to these studies the "fixed particle" theory is more probable than the "free" formation of concrements because vortex areas can only exist for short periods in renal pelvis models from healthy persons and permanently break down due to pelvicalyceal contractions.

There are a number of morphological differences between the PCS of healthy persons and of urolithiasis patients; certain PCS types might be predetermined for calculus formation from the very beginning.

Studies on geometrically and physically similar glass and transparent rubber models of PCS suggested that:

- Flow situations in the PCS vary greatly temporarily and spatially, with laminar flow dominating.
- Morphological variations in the PCS, volume flow and maximal filling pressure of the renal pelvis and sequence of concentrations exert essential influences on the flow field.
- In the PCS of healthy persons, vortices can exist only for short periods and stagnant zones are intermittently broken down as a result of adjacent directed flow.
- Under comparable flow conditions (volume flow; filling pressure), PCS of urolithiasis patients, which differ morphologically from those of healthy persons, from larger vortex and stagnant zones.
- In the experiments up to 20 times lower flow rates were found in homologous places in the PCS of urolithiasis patients. These results in forces 400 times smaller to remove particles adhering to the PCS wall in urolithiasis patients.
- Low flow rates preferentially occur in the calyx regions, particularly in the upper calyces.
- As a result of the formation of mixed zones the duration of stay for the urine in the PCS is many times longer than calculated from PCS volume and volume flow.
- According to our estimations the duration of stay for the urine might be up to 20 times longer in the PCS of urolithiasis patients than in those of healthy persons.

The tendency to urolithiasis is increased when the studies of Hajos [9], Schmidt [14], or our analyses are taken into consideration, which suggest that PCS hypomotility is frequently found in urolithiasis. Schulz et al. [23] found that in cases of urolithiasis

- pathological types of transport with reduced or even absent activity of the PCS were common,
- longer intervals between two contractions of the PCS and
- prolonged duration of contraction with very poor contractility.

The implications of these findings to diagnosis and to therapy are easier to describe than to realize. Amongst others, the therapeutic implications are

- an increase in daily urine output (here for reasons of fluid dynamics, not of physicochemistry)
- influencing the muscle tone in the renal pelvis, perhaps by stimulating α-adrenergic and cholinergic receptors
- physical activity.

The latter statement refers particularly to immobilized patients. By sitting up, contractions of the PCS are spontaneously initiated, which should be regarded as a protective measure concerning the formation of urinary calculi.

Deliberate operative morphological changes as prophylactic therapy during stone surgery may require further consideration. Diagnostically urolithiasis patients are characterized by hypomotility of the PCS, particularly in the upper calyceal groups, which may even result in functional less with regard to urine transport [23].

It has been demonstrated that pathological urodynamics and flow conditions in the PCS are important factors in the formation of urinary calculi.

The results and knowledge obtained so far shall be confirmed by further investigations and extended on further urodynamic problems of the upper urinary tract.

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