Assessing the Influence of Irrigation Flows on Clearance of Calculi Fragments During Percutaneous Nephrolithotomy: A Numerical and Physical Model Study

Amir Paster[1], Sabrina Shlain[1], Yazeed Barghouthy, Alex Liberzon, Galit Aviram, and Mario Sofer

OBJECTIVE To analyze the intrarenal hydrodynamic processes and clearance of stone fragments during percutaneous nephrolithotomy (PCNL) using numerical and physical models.

MATERIALS AND METHODS COMSOL multiphysics software was used to simulate irrigation flows and transport of particles in a kidney model based on computerized tomographic acquisition. A similarly shaped physical model with solid particles was constructed, and PCNL was simulated using nephroscopes. The particles were tracked by a digital camera. Particle clearance in both models was compared at various flow velocities and angles.

RESULTS The numerical model predicted a significantly increased particle clearance with high-velocity irrigation (0.25 vs 1 m/s, 12% vs 70%, respectively: $P < .0001$), as did the perpendicular positioning of the instrument (45° vs 90°, 1% vs 70%: $P < .0001$). These results were validated in the physical model with a correlation of r = 0.98. Particle clearance occurred only in the directly irrigated calyx. The flow and the particle movements in the other calices were negligible. The calculated intrarenal pressure at the maximal velocity reached 15.6 cmH_2O.

CONCLUSION Effective clearance of particles is achieved when irrigation is perpendicularly directed to the targeted calyx and enhanced by higher flow velocities. The flow in calyces that are not directly irrigated is ineffectual, and high flows do not significantly increase the intrarenal pressure. Validation of the numerical model by the physical model supports the use of computerized methods for advanced renal hydrodynamic research that may replace the need of some animal and human studies on the clearance of stones during PCNL. UROLOGY 124: 46−51, 2019. © 2018 Elsevier Inc.

Despite continuous technological advances and experience gained with percutaneous nephrolithotomy (PCNL), the rate of residual fragments as assessed by postoperative noncontrast computerized tomography has been reported in the range of 8%-22%.[1-6] This residue tends to become sediment in sunken and hidden locations of the intrarenal collecting system (eg, calyces not accessible by the nephroscope, poor intraoperative endoscopic visualization, lower calyces, etc). When left behind, it represents a nidus for the precipitation of salts, aggregation and stone formation, thus negatively affecting the clinical outcome.[7] One-half of the patients with residual fragments will suffer an acute stone event, and up to 61% of them will need a new treatment.[5] In addition to its role in providing a clear field of view, the irrigation used in PCNL contributes to the evacuation of the stone residue produced during fragmentation. While developing the concept of minimally invasive PCNL (MIP), Nagele et al[8] observed that fragments smaller than the diameter of the working sheath are engaged in the backflow created with the retrieval of the nephroscope, and referred to this process as the "vacuum cleaning effect." A mathematical model of this effect was recently proposed in a single calyx model.[9] However, that model was limited to a confined single calyceal system and therefore does not necessarily reflect the hydrodynamic processes within the entire intrarenal collecting system. Our study aimed to further

[1] *Equal contribution.*

From the School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel; the Endourology Unit, Tel Aviv Sourasky Medical Center, Sackler School of Medicine, Tel Aviv University, Tel Aviv, Israel; and the Department of Radiology, Tel Aviv Sourasky Medical Center, Sackler School of Medicine, Tel Aviv University, Tel Aviv, Israel

Address correspondence to: Mario Sofer, M.D., Department of Urology, Tel Aviv Sourasky Medical Center, Sackler School of Medicine, Tel Aviv University, 6 Weizman St., Tel Aviv 6423906, Israel. E-mail: mariosofer@hotmail.com

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analyze and define these processes using a numerical model (NM) for the prediction of PCNL intrarenal hydrodynamics and then applied a PCNL physical model (PM) to validate this prediction.

MATERIALS AND METHODS

Three-dimensional volume rendering reconstructions of a renal unit depicted from a real multidetector computerized tomographic scan were translated into geometrical data using computer-aided design software (SolidWorks, Waltham, MA; Fig. 1a). The obtained geometry was comprised of surfaces with voids unsuitable for assessing flow. Therefore, maintaining the same dimensions, contours, and proportions, the spaces were manually filled-in to achieve surface continuity. This renal shape (Fig. 1b) was used for producing a PM (Fig 1c), and an identical shape was created for an NM (Fig. 1d). The physical and numerical experiments of PCNL were carried out in models with similar geometry (Fig. 1c) accessed through a lower calyx simulating a prone position (calyx angle 30° above a horizontal plane, with slight inclination of the models to mimic a posterior-medial upper pole and an anterior-lateral lower pole). The study was performed in a university hydrologic laboratory in cooperation with engineers with expertise in physical and computerized models of flow research.

Numerical Model

An NM of flow and transport of stones was developed using commercially available software, COMSOL Multiphysics (COMSOL, Inc., Palo Alto, CA). This software is a general-purpose platform for modeling and simulating physical problems. The simulation consisted of 2 separate steps: (1) solving for the irrigation flow, and (2) solving for the movement of particles over time. The results of the flow simulation in step 1 were used as an input to the transport simulation in step 2. The nephroscope was located in the lower calyx, and its angle was related to

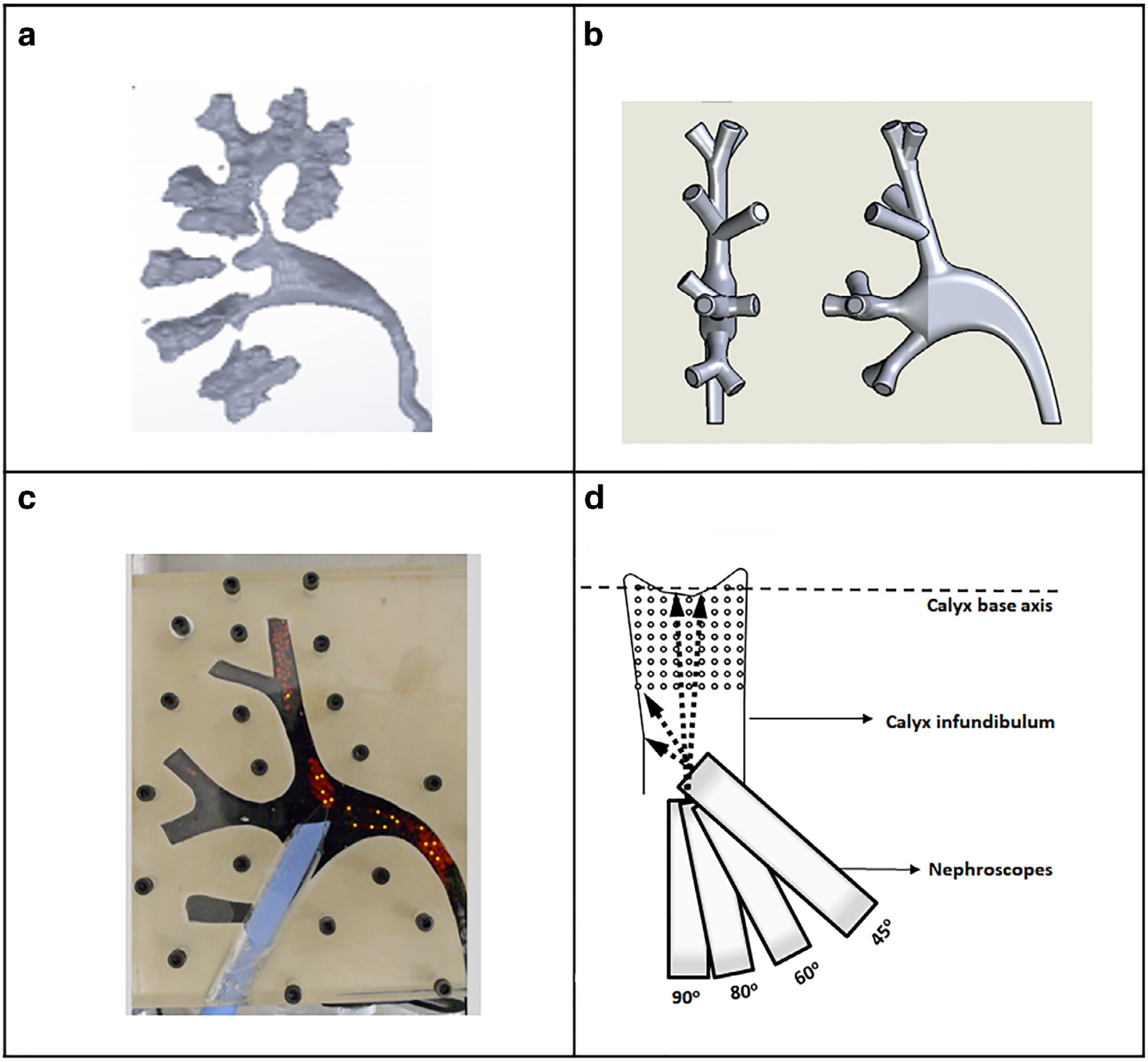

Figure 1. (**a**) CT scan of an intrarenal collecting system (ICS) after graphical manipulation with CAD. (**b**) 3D simplified ICS model. (**c**) The physical model. (**d**) Schematic presentation of nephroscope positioning and flows (dashed arrows) in the various angles assessed in the study. (Color version available online.)

the bottom (ie, papilla) of the treated calyx, and it was defined as the irrigation angle θ.

Flow Model

The flow was modeled as a quasi-steady turbulent flow of an incompressible fluid based on the typical velocity of the flow and the size of calyces. Turbulence was modeled using the Reynolds Averaged Navier-Stokes k-ε model.[10] The model solves for the average velocity $\mathbf{u}(\mathbf{x})$, the pressure field $p(\mathbf{x})$, and the turbulent kinetic energy $k(\mathbf{x})$, with $\mathbf{x}$ representing the position vector within the simulation domain. The boundary conditions were a uniform flow velocity at the inlet, a uniform pressure at the outlet, and a no-slip condition at the model walls.

Transport Model

For calculating the movements of stones within the kidney, we assumed that: (1) the effects of gravity are negligible due to relatively fast flow in the irrigation process; (2) for the sake of simplicity, the stones are hard spheres of uniform diameter d_s and density ρ_s. While stone shape may play a role in their transport, it is assumed that this effect is minor; (3) the interaction between the stones and the model boundary is elastic; (4) particle-particle interactions can be neglected since the stone residual volume is smaller than the calyx volume.

Physical Model

The PM model was covered by a transparent, hermetically fitted plate to allow quantitative video monitoring of the particles' movement while simulating PCNL in various intrarenal locations (Fig. 1c). Additional technical information for similar models is given elsewhere.[11,12] Spherical 2-mm diameter particles mimicking stones were manually inserted into the calyces similarly to that of the numerical model. The flow pressure and velocity were controlled by changing the height of the fluid supply tank (cmH_2O) relative to the PM. Rigid 24 FR and flexible 15.5 FR nephroscopes were used through a 28 Fr access sheath positioned in the lower calyx. The rigid nephroscope was oriented at a constant angle as close to the infundibulum as possible, limited by the internal geometry of the simulated collecting system. The flexible nephroscope allowed the entrance of the calyces in various angles and changes in flow angles in relation to the calyceal axis. The flow rate, velocity, and a respective dimensionless Reynolds number (defined as a rate of the velocity times diameter of the nephroscope outlet to the kinematic viscosity of the liquid, $Re = \frac{Ud}{\nu}$) are shown in Table 1. Each experiment was 2 minutes long. Motion of the particles was recorded on video and analyzed by a custom-made image processing code using Matlab (Mathworks Inc., Natick, MA). The remaining fraction of stones was estimated based on the segmentation of particles from the background and on counting the number of pixels of the identified objects relative to the first video frame.

Changes of intrarenal pressure as a result of the increments in the flow velocity were calculated for the renal pelvis, with the nephroscope located in front of the infundibulum.

Statistical Assessment

Chi-square Automatic Interaction Detector and Classification and Regression Tree analyses were performed in order to identify patterns and interactions between time, velocity, and angle. A general linear model was used to describe the association between time, velocity, angle, and their interactions with the cleaning process. All statistical tests were 2-tailed, and $P < .05$ was considered statistically significant. All statistical analyses were performed using SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.)

RESULTS

The simulations are presented in Fig. 2. The NM revealed that clearance of particles from the system is negligible at an irrigation angle of 45°. An effective clearance started at an angle of 80°, with maximal effectiveness at 90° (Fig. 2A). When assessing the influence of velocity, the minimal level at which clearance began was 0.5 m/s, with maximal effectiveness at 1.00 m/s (Fig. 2B). The evolution in time of the particles in the numerical model is illustrated for an irrigation angle of 90° at 2 different irrigation velocities (0.25 and 1.00 m/s) in Fig. 3. The variability in velocities, which were maximal around the nephroscope tip, had a return main flow out, while the velocity in most of the system was slow, particularly at the bottom of the calices. The comparison between the NMs and PMs in terms of fragment clearance in time at a given flow velocity yielded no significant differences ($P > 0.05$), for a correlation coefficient of $r = 0.98$ (Table 2).

Calculation of the intrarenal pressure as a result of increasing irrigation pressure up to 130 cmH_2O to produce a velocity of 1 m/s resulted in a very mild increase in the intrarenal pressure (Fig. 3). Classification and Regression Tree analysis showed the relative contribution of the irrigation angle, flow velocity, and duration of treatment to the stone clearance (Fig. 4). The general linear model revealed that any increase of an angle above 60° (range 60°-90°) and/or velocity above 0.25 m/s (range 0.25-0.75 m/s) significantly improved the clearance of stones ($P < .000$). However, further increase in velocity to 1 m/s (the maximal tried value) failed to result in any significantly improved clearance in comparison to 0.75 m/s ($P = .181$).

DISCUSSION

Since its first description in 1976,[13] PCNL evolved as the standard procedure for treating large and complex calculi, completely replacing open stone surgery. The establishment of the procedure was supported by innovations in puncture, dilation and retrieval devices, improvement in fluoroscopic and ultrasonic imaging, developments in powerful stone fragmentation technologies, and newly designed rigid and flexible scopes with enhanced image transmission and better ergonomic design.[14] In addition, research was conducted in order to avoid hydrodynamic-related deleterious effects, which could result in electrolyte disturbance, hypothermia, and septicemia.[15-17] However, issues related to the cleaning effect of the irrigation component have not yet been systematically analyzed. The so-called "vacuum cleaning effect" has been recently described, and its mathematical model has been reported in a single calyx setup.[8,9] Those observations led to the creation of the MIP system (Karl Storz, Tuttingen, Germany), which was shown to be effective for the treatment of small stones located in relatively close spaces (eg, calyces, small renal pelvis, diverticulae, etc). That single calyx model was used for the assessment of flows

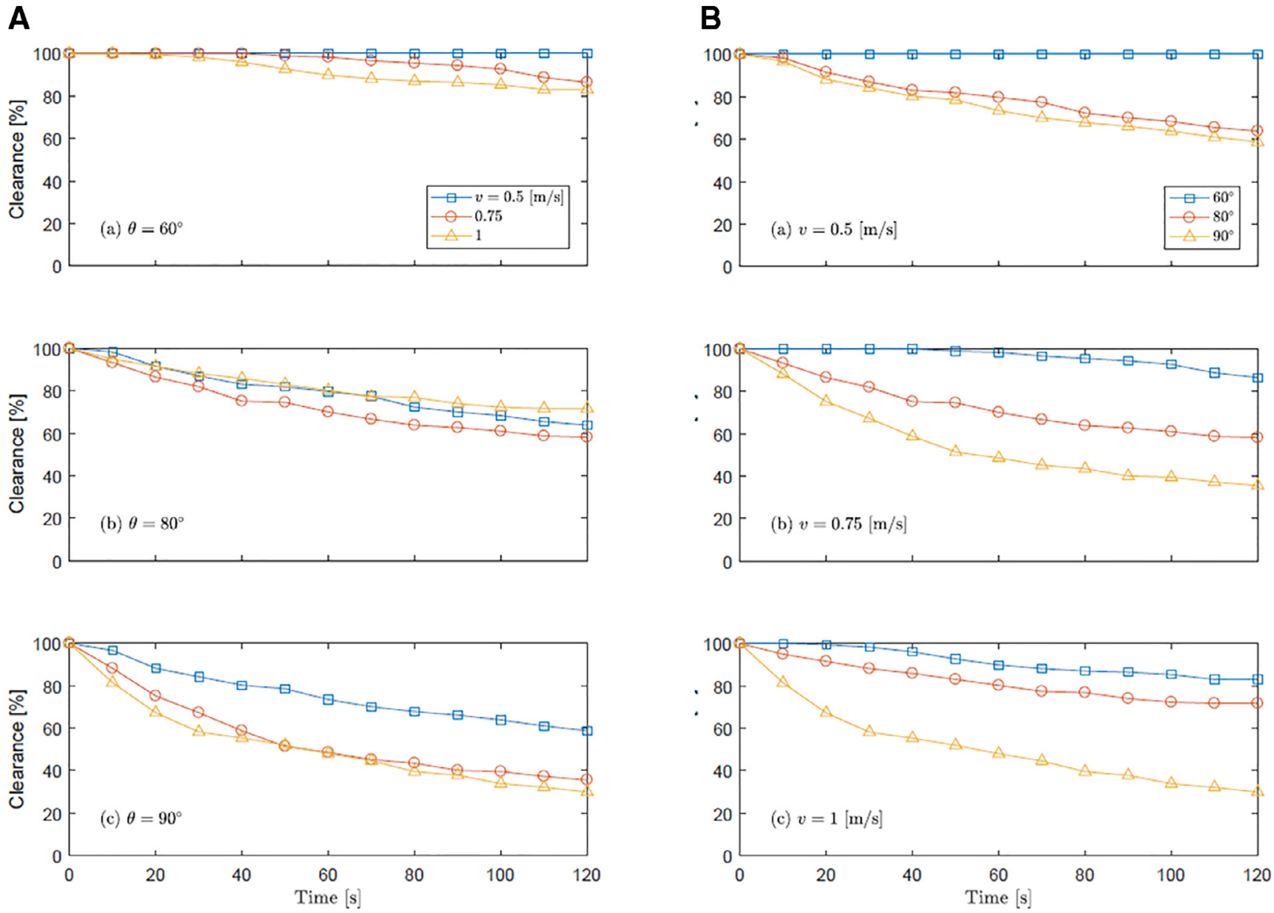

Figure 2. Fraction of remaining particles in the numerical model as a function of: (**A**) irrigation velocity at different irrigation angles ($\theta = 60^\circ, 80^\circ, 90^\circ$) and (**B**) irrigation angle at different velocities (v = 0.5, 0.75, 1.00m/s).

with both MIP and standard nephroscopes under those conditions.[8,9,15,16] However, in our opinion, it does not reflect the hydrodynamic process of the entire intrarenal collecting system. The transport of a kidney stone within the intrarenal collecting system is a complex phenomenon that is primarily driven by the flow-induced drag force as well as by interactions with the surroundings. The rationale of our current study was to extend the existing research to include a simulated complex anatomical situation of a complete intrarenal collecting system with multiple calyces and infundibulae positioned in various angles as depicted from a real computerized tomographic scan. This configuration better mimics a real-life PCNL performed for complex and large stones, and additionally deals with the problem of residual fragments in multiple peripheral locations. These fragments are trapped in zones with stagnant fluid and have a limited probability to be suspended and cleared out with the nephroscope return flow, thus increasing the risk for recurrent stones and the need for ancillary procedures.[4,5]

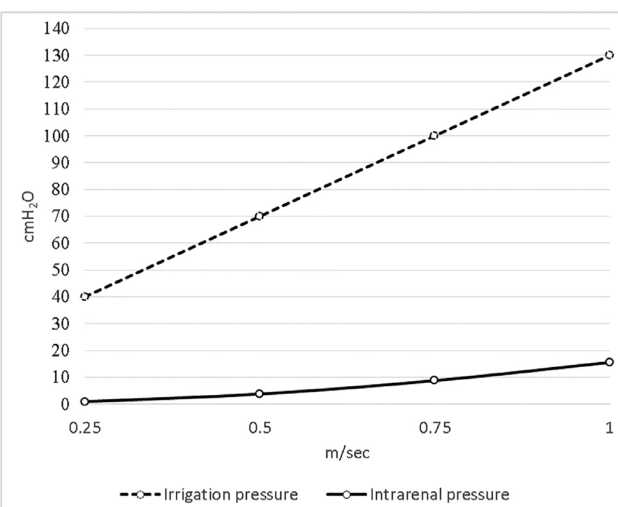

Figure 3. Changes of intrarenal pressure in relation to increasing irrigation pressure in order to produce the selected velocities for the experiments (0.25-1 m/s).

Our concept of using numerical simulation of a flow in this complex geometry along with tracking virtual particles that undergo flow drag and elastic interaction with the calyx boundaries is unique. The work on a PM with similar geometrical and physical conditions as those of the NM and the high correlation that resulted between these 2 models provide strong support to the proposal that the NM can be used for further experiments on intrarenal hydrodynamics. The results of our

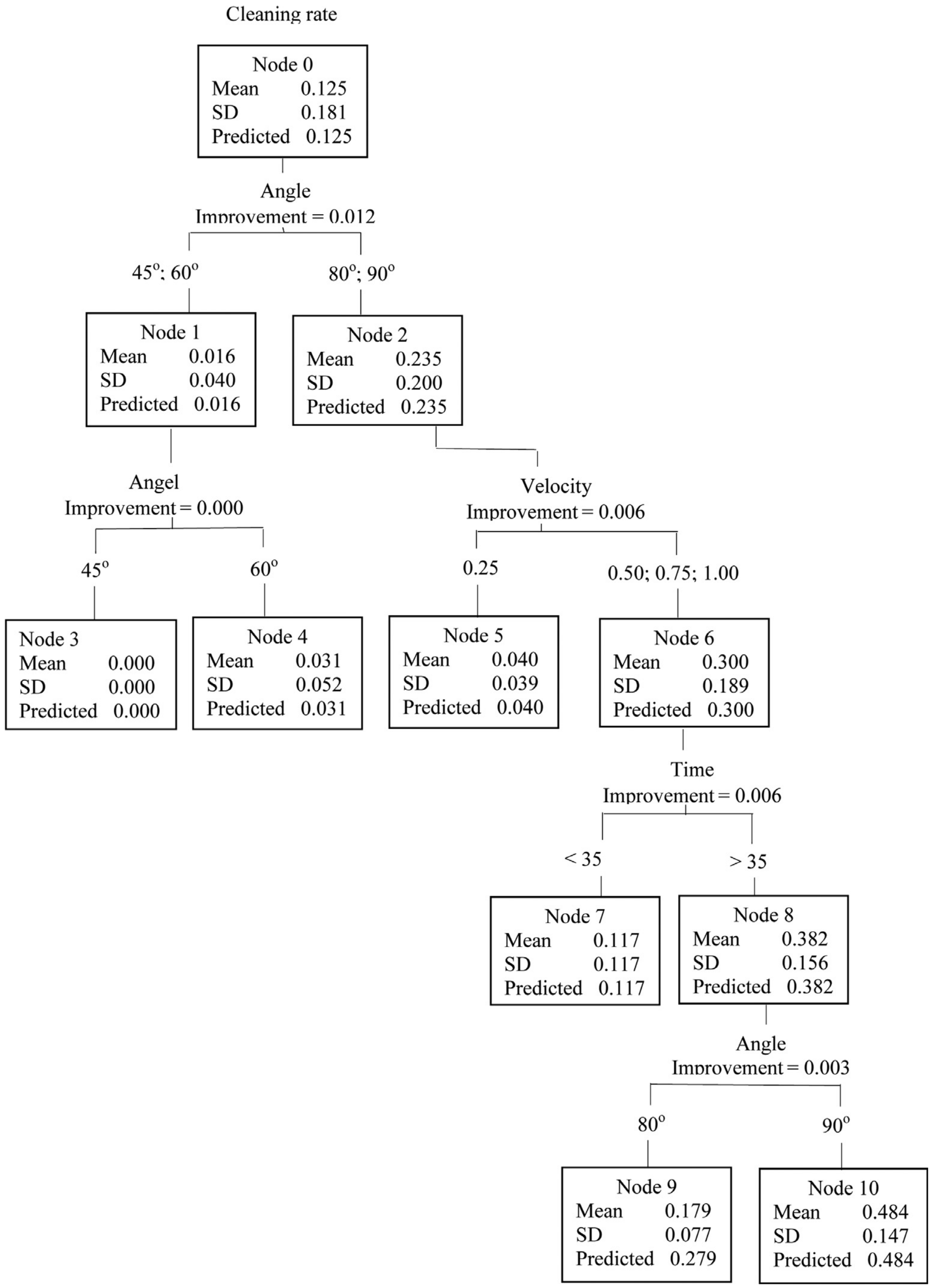

Figure 4. Classification and Regression Tree (CART) analyses showing patterns and interactions between time, velocity, and angle.

study revealed that the effectiveness of the clearance process is enhanced by the flow velocity and the perpendicular direction of the irrigation. The turbulent flow produced at the tip of the nephroscope may contribute to the clearance of fragments located in proximity to it; however, the key parameters for increasing the amount of stone clearance are the direct irrigation with high-velocity flows within each calyx. These findings support the mandatory use of flexible scopes that may negotiate any anatomical locations in multiple angles. Although we could demonstrate that clearance effectiveness is enhanced at high-flow velocities, its clinical applicability could not be determined without the assessment of the intrarenal pressure. The obvious potential deleterious clinical effects related to performing PCNL at high intrarenal pressures precludes such trials. However, assessment of the relation between velocity and intrarenal pressure resulted in a maximal pressure of 15.5 cmH_2O at a velocity of 1 m/s produced by an irrigation source located 130 cm above the model level. This can be considered low intrarenal pressure and it is acceptable during PCNL procedures.

We are aware that our study may have limitations. One of them might be the difference between the NM and PM in terms of interaction elasticity. While the NM considered it as being elastic, the PM had rigid boundaries. In addition, we used idealized spherical particles to simulate fragments in both simulations, shape that is not similar to the irregular forms of fragments produced after lithotripsy. These issues should be further assessed in a PM using real kidneys. Finally, gravitational forces related to mass and the use of various intrarenal configurations might need more investigation to assess their potential influence. Despite these limitations, we believe that our results contribute to the understanding of the intrarenal flows and movement of particles during PCNL, and that they open new horizons in the study of hydrodynamics, instrument design, and computerized modalities of research in this setting. This computerized platform with or without the combination of the PM can be easily integrated for research of additional data. As an example, we plan to further assess flows and stone clearance in different patient positions (supine vs prone), particular kidney anatomical characteristics (malrotation, horseshoe kidney, fusion, ectopy, etc), various intrarenal configurations, optimal relation between the instrument and the working sheaths sizes, risks of fragments' migration through the uretero-pelvic junction and various features of the irrigation fluid (different viscosities and flows).

The importance of this work lies in its assessment of intrarenal flows in an entire intrarenal collecting system and of the potential use of computerized models for research when clinical studies are not ethically feasible. It provides a calculation of the intrarenal pressure as a result of increasing the flow velocity within the system. In addition, it demonstrates the most effective position of the nephroscope in relation to the target in order to increase the effectiveness of stone clearance during PCNL. Based on these unique findings, we recommend the use of flexible nephrosopes for direct calyceal irrigation in order to enhance fragment clearance during PCNLs.

In conclusion, endoscopic surveillance of each calyx perpendicularly and with high intrarenal flows may improve the clearance of calculi fragments and subsequently increase the stone-free rates of PCNL. The results of our study and their high correlation with the PM may promote the use of the NM for research on the clearance of calculi fragments during PCNL in place of animal and human experimental studies.

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SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.urology.2018.10.007.

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