Original Article

Current Urology

Special Topic: Advances in Urinary Calculi Management

OPEN

Role of virtual reality in improving the spatial perception of the kidney during flexible ureteroscopy: A feasibility study using virtual reality simulators and 3D models

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Abstract

Background: The aims were to describe a software-based reconstruction of the patient-specific kidney cavity intraluminal appearance via a head-mounted device and to estimate its feasibility for training novices.

Materials and methods: In total, 15 novices were recruited. Each novice was shown a three-dimensional reconstruction of a patient's computed tomography scan, whose kidney was printed. They then joined the surgeon in the operating room and assisted them in detecting the stone during flexible ureteroscopy on the printed model. Then, each participant did a 7-day virtual reality (VR) study followed by virtual navigation of the printed kidney model and came to the operating room to help the surgeon with ureteroscope navigation. The length of the procedure and the number of attempts to find the targeted calyx were compared.

Results: With VR training, the length of the procedure ($p = 0.0001$) and the number of small calyces that were incorrectly identified as containing stones were significantly reduced ($p = 0.0001$). All the novices become highly motivated to improve their endourological skills further. Participants noticed minimal values for nausea and for disorientation. However, oculomotor-related side effects were defined as significant. Five specialists noticed a good similarity between the VR kidney cavity representation and the real picture, strengthening the potential for the novice's education via VR training.

Conclusions: Virtual reality simulation allowed for improved spatial orientation within the kidney cavity by the novices and could be a valuable option for future endourological training and curricula.

Keywords: Ureteroscopy; Kidney calculi; Virtual reality; Endourology; Training; Nephroscopy; 3D

1. Introduction

Endoscopic skills are vital in urology residency training. However, the steep learning curve and the need for patient safety warrant training beyond the operating room (OR).[1] Virtual reality (VR) simulators provide high-fidelity three-dimensional (3D) virtual models for mastering necessary skills without time constraints and ethical concerns and could be a solution for the abovementioned worries. There have been numerous studies on using VR simulators in teaching and planning endoscopic kidney stone treatment.[2–5] However, most were mainly focused on the initial stages of endourological procedures using anatomical templates at a high price, or they did not use the head-mounted device (HMD) to thoroughly immerse the user in an interactive environment, restricting their active implementation both in clinical practice and routine novice education. Besides, spatial orientation skill is necessary for mastering surgery in closed cavities, such as the pelvicalyceal system (PCS). However, only a few VR-based simulators allow for conducting a detailed study of the internal appearance of the template renal cavity.

This study aimed to describe the use of a mobile software-based reconstruction of a patient-specific kidney cavity intraluminal appearance supplemented with a VR function via HMD and to estimate its feasibility for training novices to improve their spatial perception.

2. Materials and methods

2.1. Pre-education assessment

After ethical committee approval (ERN1032), 15 novices with neither experience in self-performing nephroscopy nor experience with VR headsets were recruited; 5 were final-year medical students, 7 were first-year urology residents, and 3 were second-year urology residents. To minimize their knowledge difference, we gave all of them lectures

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Current Urology, (2024) 18, 1, 24–29

Received February 13, 2023; Accepted April 13, 2023.

http://dx.doi.org/10.1097/CU9.0000000000000207

by a senior urologist on the PCS anatomy, classification of kidney stones, and indications for their removal. The total duration of lectures was 2 hours. These were delivered just before the practical element. At the end of the lectures, each participant underwent a one-to-one oral test on the subject matter. Where questions were answered incorrectly, the lecture material was explained further to that individual.

In addition, a silicone kidney model of a patient without kidney stones was printed on Stratasys Fortus 400mc printer (Stratasys, Inc, Eden Prairie, MN, USA) and prepared for the flexible ureteroscopy (fURS) training. Briefly on its manufacture, the soluble PCS model was created from polylactic acid and placed in the negative kidney mold, followed by the filling with mixed (0-30-Shore) red silicone and left for its congealing. The obtained kidney model was immersed in acetone to dissolve PCS. Malecot catheter 30 Fr was then inserted to imitate the ureter. We decided not to create printed ureters to simplify the model preparation process. Such a silicone kidney model cost $75, and manufacturing took 24 hours. It should be noted that the focus of the study was the VR simulator, and information on the printed model and manufacturing is only given to describe the study design better.

After the lecture, each novice was shown the 3D reconstruction of the computed tomography (CT) scan of the patient whose kidney was printed. The kidney cavity was chosen specifically without any stones to put a mark on the 3D picture, according to which novices were informed that the stone was there. Each calyx was numbered, and the selection was carried out randomly in each case via www.random.org (Fig. 1).

Afterward, they joined the surgeon in the OR and assisted them in navigating inside the kidney cavity during fURS to detect the stone. During fURS, the surgeon (a senior urologist) used the Litho-Vue flexible ureteroscope (Boston Scientific, Marlborough, MA, USA) on the silicone model to detect the stone (Fig. 2). In all cases, the stone was placed without notifying the surgeon of its location. The length of endoscopy was calculated from the beginning to finding the stone and the number of small calyces examined before finding the stone was noted.

2.2. *Virtual reality education*

Computed tomography–urography scans of 4 patients with PCS corresponding to the 4 types of the kidney cavity according to Sampaio classification were extracted from the local database. In addition, scans of 2 other patients with horseshoe and duplex kidneys were collected. In all cases, PCS was reconstructed in 3D, separately saved as a stereolithography (STL) file, and smoothed via Blender (National Institute of Health, Bethesda, MA, USA), followed by the transmission of the files to the smartphone. A learning curve was associated with creating the STL models: initially, this task required 5–10 minutes; however, after the first 3–5 models, the file-preparation time was 2–3 minutes. All patient-specific data were automatically removed during STL file creation, providing data security and anonymity. The Sampaio classification groups

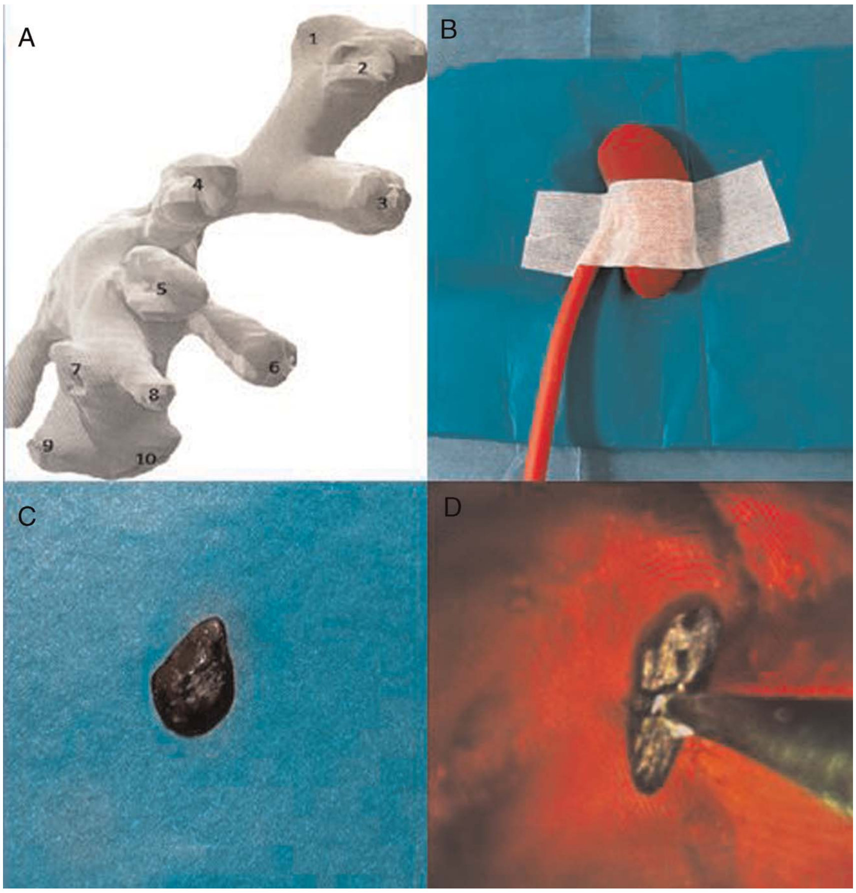

Figure 1. (A) The 3D reconstruction of the kidney cavity used in our study with numbered minor calyces. (B) Printed silicone kidney to imitate fURS before and after VR curriculum. (C) The kidney stone model used in our study (diameter: 5 mm). (D) Endoscopic view of the stone placed by the basket according to its randomly defined location. fURS = flexible ureteroscopy; VR = virtual reality.

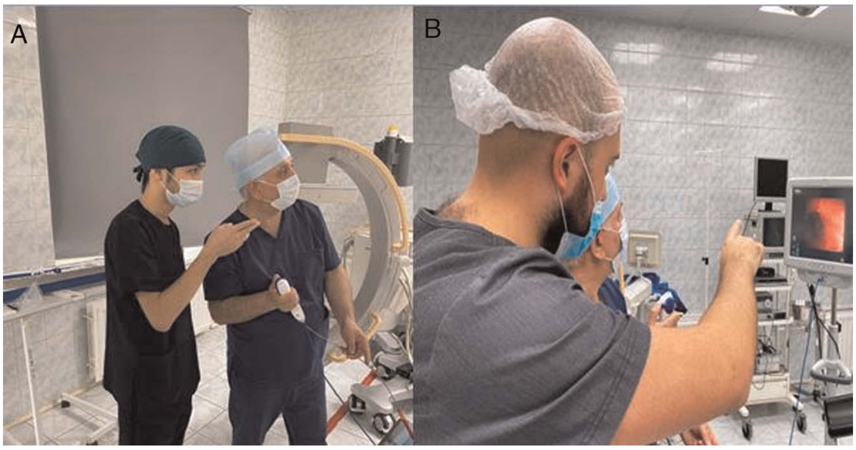

Figure 2. Novices guide a senior urologist to find the stone before virtual reality education. (A) Novice no. 2. (B) Novice no. 5.

PCS into 2 main categories: A and B.[6] These are further subdivided into AI/AII and BI/BII. These cover a range of different calyx morphologies and drainage pattern combinations.

The basis for this work was the InsKid application developed using C# programming language for Android OS-based smartphones, described previously.[7] After opening the STL file with the kidney cavity, it may be represented via 2 regimes: two-dimensional (2D) and VR modes. In the former, internal and external 3D reconstruction of the kidney cavity are displayed on the left and right windows of the smartphone, respectively. The red triangle at the right window reflects the actual user's position and the view direction. Either via wire or wirelessly, the image from the smartphone could be transferred to the monitor, making endoscopy simulation much more convenient. During VR mode, the user sees an external reconstruction of the kidney cavity, after which it is possible to enter it anywhere and move inside the cavity. After getting into the cavity, it is impossible to get out of it; therefore, when preparing these models, we cut off a part of the proximal ureter to create a virtual hollow enabling users to exit the kidney cavity for its external study.

The control was carried out using a PS4 controller connected to the phone via Bluetooth and was bought for $20. In the 2D mode, the right and left joysticks were responsible for moving along the plane or changing the view direction, respectively. In the VR mode, the right joystick was responsible for the same, whereas the view direction corresponded to the head movements. In both settings, it was possible to visualize kidney stones, which can be prepared similarly to that described for the PCS models. In addition, it was possible to manually create different virtual shapes imitating kidney stones as we did via Blender software. For smooth execution, the app was run in the Samsung A51 equipped with Exynos 9611 CPU, 4 GB memory, 512 GB SSD, and Mali-G72 MP3 graphics accelerator. Virtual reality box 3D Virtual Reality Glass with a lens diameter of 42 mm was bought for $15 and used for the smartphone placement and immersive visualization of the kidney cavity.

At the beginning of the training, the phone with the installed application was wirelessly connected to the laptop to familiarize novices with the basic principles of the InsKid work via 2D mode. Then, the same was done for the VR mode. The VR education was provided by the senior urology resident (T.A.) responsible for the app development under the supervision of a senior urologist. The former was neither included in the statistical analysis nor included as a participant in this study to obviate associated biases (Fig. 3).

Then, each participant studied all kidney cavities extracted from the local database via VR mode for 15 minutes daily for a week to familiarize themselves with the VR approach. In addition, any VR-related side effects were noted via the simulator sickness questionnaire.[8] It should be noted that novices performed no reading, training, or education besides the HMD software curriculum during the study.

2.3. *Study endpoints*

Because we were focused on evaluating the improvement in spatial orientation within PCS, the primary endpoint was the number of mistakes when novices guided the senior urologist to check the calyx. In addition, because confidence in PCS anatomy understanding logically leads to faster identification of stone-containing calyx, we estimated the length of nephroscopy as the secondary endpoint.

2.4. *Posteducational assessment*

After the VR-educational week, each trainee virtually inspected the printed PCS (in 10 min). Then, each participant assisted the senior urologist in navigating inside the kidney cavity during fURS to find the stone, which was placed per the VR reconstruction, and with the senior urologist blinded about the stone's location.

The duration of endoscopy and the number of small calyces examined before the discovery of the stone were recorded and compared with pretraining results. Moreover, the motivation of the subjects to develop endourological skills was further evaluated. If it increased, novices were also asked whether the increase was caused by using the immersive HMD curriculum, participation in this study, or due to the willingness to become a competent endourologist.

At the end of the study, 5 dedicated specialists with experience of at least 50 ureteroscopy cases were recruited. They evaluated the VR picture of different extracted PCS to ascertain the face (similarity of virtual reconstruction with a real endoscopic picture during surgery) and content validity (assessing the usefulness of integrating VR into the training program of inexperienced specialists) of the InsKidVR. At the end of the study, the novices were asked whether they became encouraged by the educational tool and were motivated to master endourological skills further via a yes/no answer.

2.5. *Statistical analysis*

SPSS statistical software version 26.0 (IBM, Chicago, IL, USA) was used for statistical analysis. Continuous data were presented as a

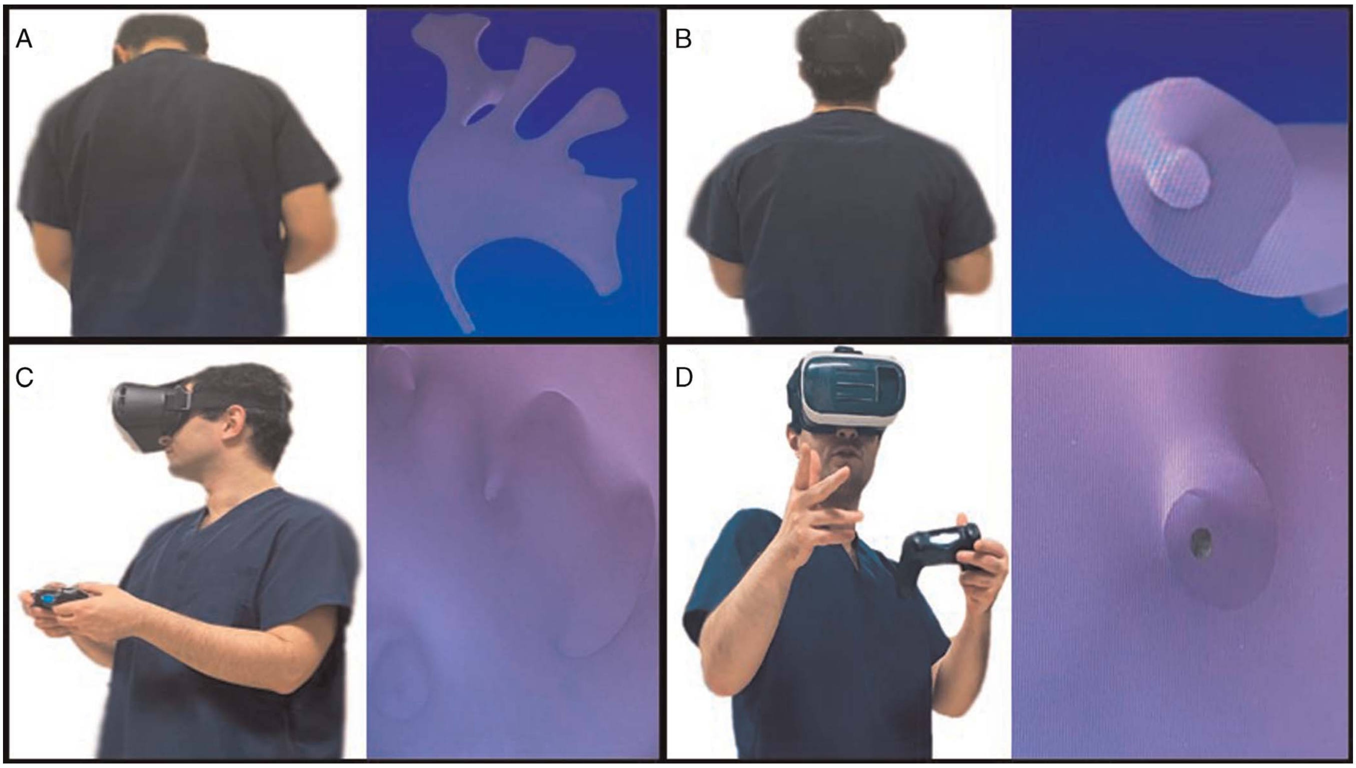

Figure 3. A senior resident providing novices with the lecture on InsKidVR usage with the wireless translation to the laptop. (A) VR investigation of the external PCS view. (B) Manually created ureter to move inside PCS. (C) Investigation of the middle and lower calyceal groups. (D) Investigation of the small calyx from the upper group containing virtual stone. PCS = pelvicalyceal system; VR = virtual reality.

mean and standard deviation (SD) or median and minimum and maximum value according to data distribution, which was assessed via the Kolmogorov-Smirnov test. The pretraining and posttraining novice results were compared using the Wilcoxon test. Nominal data were compared via the χ^2 test. Face and content validities were evaluated via the Likert scale (1–5). A significant difference was considered as $p < 0.05$.

3. Results

The results are presented in Table 1. According to distribution, the length of endoscopy and the number of mistakenly checked calyces were described as mean (±SD) and median (min–max), respectively. The mean (±SD) length of nephroscopy was significantly reduced (33.4 ± 12.6 vs. 13.1 ± 4.3 seconds; $p = 0.0001$), as well as the number of small calyces that were incorrectly identified as containing stones before finding the correct one (2 [1–4] vs. 0 [0–1]; $p = 0.0001$), which indicates the usefulness of VR inspection of the kidney cavity before its endoscopic examination. Five novices were left-handed (no. 2, 4, 10, 12, 14).

In addition to improving objective parameters, all novices become highly motivated to improve their endourological skills further (15/15). The results of the simulator sickness questionnaire showed minimal values for nausea (5.45 ± 1.9) and disorientation (6.11 ± 2.03), whereas oculomotor-related side effects were defined as significant (12.15 ± 2.7). However, participants could cope with such symptoms. Five recruited specialists noticed a good similarity of PCS reconstructed with natural picture (4/5). Meanwhile, some aspects were different: wall homogeneity without vascular contour and stable dilated state of the PCS, not imitating dynamic expansion during nephroscopy. Specialists also appreciated the potential

Table 1

Novices' results before and after introducing the VR curriculum.

	No. novices																
Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Mean ± SD/median (min–max)**	***p***
Nephroscopy length, s																	0.0001
Before VR study	29	23	18	52	21	19	55	41	47	30	29	19	33	46	39	33.4 ± 12.6	
After VR study	11	8	10	15	11	8	12	17	12	20	15	10	9	21	18	13.1 ± 4.3	
No. incorrectly chosen calyces																	0.0001
Before VR study	3	1	2	4	3	3	2	4	1	3	3	2	2	1	3	2 (1–4)	
After VR study	0	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0 (0–1)	

SD = standard deviation; VR = virtual reality.

of VR for the novices' education (4/5) to orient themselves within PCS spatially.

4. Discussion

In contemporary surgical training, there continues to be a push for skill mastery beyond the clinical setting.[9] This has certain benefits, such as increasing the volume of exposure acquired by the surgical trainee while minimizing novices' impact on patients. The training process must accommodate limited learning possibilities due to reduced work hours, attention to reducing medical errors, and bounded subsidy. Currently, medical technologies are developing faster than ever, and inadequate training can create significant gaps in the skills of young specialists.

Many simulators are available for endourological mastering, divided into biological, nonbiological, and VR, depending on the manufacturer.[10] Although physical trainers provide an appropriate haptic response, the effect on the training of novices is analogous compared to virtual simulators. Furthermore, the VR models can present more anatomical variants for education, thus enhancing the trainees' confidence.[11] In addition, the VR-based approach makes it possible to master skills more cost-effectively because it is not required to use fragile or expensive endourological tools, which fail or break more frequently at the beginning of the learning curve.[12]

For trainees, VR-based training proposes unrestricted, repeatable mental skills acquisition in a stress-free setting before their first patient exposure. It was assumed that VR should become an essential part of the education and attestation of surgeons.[13] We have used this, having various technological advances and new tools that were previously unavailable. Currently, different approaches exist to using VR in simulated training.

UroMentor™ (Simbionix, Cleveland, OH, USA) is a non-HMD computer-based VR system that has been validated for training cystoscopy and flexible ureteroscopic stone extraction.[2,3] PERC Mentor™ Simulator (Simbionix, Cleveland, OH, USA) is also a non-HMD VR simulator designed to train fluoroscopic-guided percutaneous access to the kidney cavity. According to Noureldin et al.,[4] it is possible to differentiate between competent and noncompetent trainees using PERC Mentor™ via a global rating score. Marion Surgical K181 is an HMD VR surgical simulator that allows users to interact with patient anatomy via details obtained from CT scan images in a virtual OR. It provides users with haptic feedback while they control the C-arm and a puncture needle.[5] Finally, Parkhomenko et al.[5] described the HMD approach to build patient-specific VR models that immerse the user in an interactive simulation of the patient's renal anatomy. It is possible to segregate and visualize all anatomic structures, such as bones, vessels, renal parenchyma, the kidney cavity, stones, and adjacent organs.

Virtual nephroscopy is feasible in 3 of the mentioned simulators. Meanwhile, only our technology provides truly cost-effective use of VR at an affordable price for investigating patient-specific kidney PCS.[5] This is a very important fact that directly contributes to the availability of technology implementation in clinical practice and in routine training of novices with the possibility of using it even at home, where all they need is an Android OS-based smartphone and VR glasses. According to Moran et al.,[14] gamification increases resident engagement in robotic surgical training, with the same application in the presented study. According to our results, all participants became more motivated to master endourological skills further. Indeed, VR-based HMDs seem to be a valuable constituent of medical education and can be advised as an additional tool for teaching and learning particularly complex spatial structures.[15] This is not surprising as the younger generation is more familiar with various digital devices and technologies and is more often interested in computer games, including via VR glasses. According to Tan et al.,[16] younger participants attained higher VR performance scores and shorter completion times when performing common daily activities. In this regard, their hobbies and medical training should be integrated, catering to their strengths and interests rather than separated.

Some studies described the disadvantages of HMDs, such as motion sickness, nausea, technical problems, and stress. Current-generation VR HMDs cause significantly fewer side effects than old versions.[17] This fact suggests that the frequency of side effects in our study may be reduced by using more modern glasses, which is an area of future research.

The limitations of this study include the small number of recruited novices and a short study length. A larger study sample could allow for comparison between different educational experience levels, for example, medical students versus urology residents. In addition, a more intensive training period might have increased the effect of VR-nephroscopy integration in the education process. We did not include the control group to clarify whether the same effect may be obtained via 3D PCS reconstruction or only assisting during fURS training. The movements within PCS were performed via head movements and controller, which is quite far from the manipulation of the endoscopic instruments. However, the primary goal was to describe InsKidVR and estimate its feasibility for integration into novices' education to improve their spatial perception within PCS. That is why the results of left- and right-handed novices were not compared. This is not exhaustive of how this technology can be used. The future use would be creating a flexible ureteroscope-like controller to create an adequate platform for the trainees' psychomotor skills improvement. Although this is not the purpose of this study, this technology may have more merit in understanding small kidney lesions going for partial nephrectomy or percutaneous ablation. This feasibility study proved the effectiveness of such training on the novices' skills and is an argument for the following randomized study with sufficient involved subjects.

5. Conclusions

Virtual reality and the described InsKidVR simulator enable improved spatial orientation within the kidney cavity when used by novices. This could be a valuable option for endourological training and adoption in formal didactic curricula.

Acknowledgments

The authors thank Boston Scientific for the single-use flexible ureteroscopes LithoVue and stone models provided for the study.

Statement of ethics

This study was approved by Mariinsky Hospital, Saint Petersburg, Russia, with an ethical approval number ERN1032. Informed consent was obtained from all individual participants included in the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Conflict of interest statement

The authors declare they have no conflicts of interest

Funding source

None.

Author contributions

AT: Design and conduct of the study, collection of the data, management of the data, analysis, interpretation of the data, preparation, review and approval of the manuscript;
BMZH, UZ MSS: Collection of the data review, analysis, interpretation of the data, preparation and approval of the manuscript;
NN, MS, AS, BG: Collection of the data review, interpretation of the data and approval of the manuscript;
PJ-J: Interpretation of the data, editing, review and approval of the manuscript, supervision;
BKS: Review and approval of the manuscript, supervision.

Data availability

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

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How to cite this article: Talyshinskii A, Hameed BZ, Zhanbyrbekuly U, Silay MS, Naik N, Shah M, Singh A, Guliev B, Juliebø-Jones P, Somani BK. Role of virtual reality in improving the spatial perception of the kidney during flexible ureteroscopy: A feasibility study using virtual reality simulators and 3D models. *Curr Urol* 2024;18(1):24–29. doi: 10.1097/CU9.0000000000000207