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ORIGINAL ARTICLE

The use of individualized 3D-printed models on trainee and patient education, and surgical planning for robotic partial nephrectomies

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Abstract

3D printing is a growing tool in surgical education to visualize and teach complex procedures. Previous studies demonstrating the usefulness of 3D models as teaching tools for partial nephrectomy used highly detailed models costing between $250 and 1000. We aimed to create thorough, inexpensive 3D models to accelerate learning for trainees and increase health literacy in patients. Patient-specific, cost-effective ($30–50) 3D models of the affected urologic structures were created using pre-operative imaging of 40 patients undergoing partial nephrectomy at Thomas Jefferson University Hospital (TJUH) between July 2020 and May 2021. Patients undergoing surgery filled out a survey before and after seeing the model to assess patient understanding of their kidney, pathophysiology, surgical procedure, and risks of surgery. Three urological residents, one fellow, and six attendings filled out separate surveys to assess their surgical plan and confidence before and after seeing the model. In a third survey, they ranked how much the model helped their comprehension and confidence during surgery. Patient understanding of all four subjects significantly improved after seeing the 3D model ($P<0.001$). The urology residents ($P<0.001$) and fellow ($P<0.001$) reported significantly increased self-confidence after interacting with the model. Attending surgeon confidence increased significantly after seeing the 3D model ($P<0.01$) as well. Cost-effective 3D models are effective learning tools and assist with the evaluation of patients presenting with renal masses, and increase patient, resident, and fellow understanding in partial nephrectomies. Further research should continue to explore the utility of inexpensive models in other urologic procedures.

Keywords 3D · Medical education · Partial nephrectomies · 3D printing · 3D models

Abbreviations

RAPN	Robot-assisted partial nephrectomy
3D	Three-dimensional

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Introduction

Partial nephrectomy is the gold standard treatment for small renal masses and robot-assisted partial nephrectomy (RAPN) has become a well-established surgical technique. RAPN requires a thorough understanding of three-dimensional (3D) renal anatomy to appreciate the configuration of the renal artery(ies) and vein(s), the tumor's location and depth, and the edges of the collecting system. This knowledge facilitates optimal outcomes including reduced warm ischemia time, lower rates of surgical margin positivity, lower blood loss, and shorter operative times. Thus far, renal anatomy has been created through interpretation of two-dimensional (2D) axial imaging. This mental exercise is difficult and requires experience for accurate mental modeling. Correspondingly, it may be difficult for those without this experience, such as patients or urologic trainees, to understand renal anatomy. When quizzed on kidney physiology, anatomy, tumor characteristics, and planned surgical intervention based on CT imaging, patient comprehension has been shown to improve after being shown the 3D models [1, 2]. As shown in the field of neuroradiology, there is discordance in diagnosis and understanding of imaging in trainees versus attendings, even when 3D imaging is used [3].

Studies have reported the growing use of 3D-printed models for RAPN for pre-operative planning and education with potentially improved clinical outcomes [4–7]. However, most of these prospective trials involved a small number of patients, [5, 6, 8, 9] prompting further investigation into the role of 3D models in larger populations. Furthermore, the majority of the studies describe models with expensive production costs ($250–1000) [1, 6, 8, 10] which may not be feasible to produce on a regular basis [11]. A Japanese team was able to fabricate a cheaper model at an estimated cost of $10 each; however, this square block model requires over 13 h of human labor to include painting and soldering [12].

We sought to create an inexpensive 3D-printed model that contains the relevant anatomical information for RAPN (tumor, artery, vein, collecting system) and required minimal build time. We aimed to determine the usefulness of a pragmatic but inexpensive individualized model in patient and trainee education with a greater goal of establishing if these models have a viable role as a standard workflow. We additionally sought to determine if incorporating this cost-efficient model improved operative outcomes for patients. To the best of our knowledge, we present the largest prospective study using an inexpensive, easily reproducible model to help answer these questions.

Materials and methods

Thomas Jefferson University's Institutional Review Board approved the study (IRB No. 15710). All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Informed consent was obtained from all patients for being included in the study.

After a kidney tumor diagnosis had been made, patients being considered for partial nephrectomy were offered enrollment in a single center prospective study to evaluate the utility of a personalized 3D model in their care. Non-English speakers, Minors (< 18 years of age), and patients who could not consent themselves were excluded from the study.

High-resolution cross-sectional imaging with contrast was obtained for all patients. Segmentation for the creation of the 3D model was reviewed by one radiologist (V.D.).

Three-dimensional model printing

Three-dimensional renal models were made using the Ultimaker S5 3D printer using fused filament fabrication (FFF) with Polylactic acid (PLA) material. The software Materialize Mimics Innovation Suite, Materialize 3-matic, and Ultimaker Cura were used. The Ultimaker S5 printer can print two materials simultaneously. The renal arteries and veins up to the tertiary branches could be defined. The kidney models were produced in two halves, splitting the kidney along its longitudinal axis to facilitate appreciation of the tumor's depth and potential involvement of the collecting system as shown in Fig. 1. The vasculature was 3D printed separately then glued to the appropriate kidney model. The average model took 8 h to print (range 3–10 h), which was usually accomplished overnight. The cost of printing was between $30 and 50 with an additional cost of 2–4 h of human labor (including time for segmentation and post-processing work to remove supports and glue the model vasculature to the parenchyma). The print was started at least 2 nights before surgery to allow time for post-processing work.

Survey and model administration

Each patient who was scheduled to undergo partial nephrectomy was contacted in advance about participation in the study. Since most patients did not return to the office between the appointment in which they scheduled their partial nephrectomy and the day of their surgery, the models were picked up on the morning of surgery by a member of the surgical team and presented to patients on the day of surgery.

All participating patients were given a "pre-model" survey to fill out before viewing the model. The survey consisted of four questions scored on a 10-point visual analog scale related to their understanding of the kidney and the surgery they were about to undergo (Online Appendix 1). They were then shown their 3D model and the relevant anatomy by a member of the surgical team. Surgical technique and potential complications were discussed with the patient with the aid of the model. After the presentation of their model, the patients were given a second "post-model" survey which repeated the same questions and was followed by four additional questions adapted from surveys created by Bernhard et al. [1] querying if their individualized 3D model helped in comprehension of the kidney, their tumor, and the surgery they were about to undergo (Online Appendix 1). All surveys were in English and performed in person.

Members of the surgical team filled out three surveys. The surgical team consisted of the attending, a senior

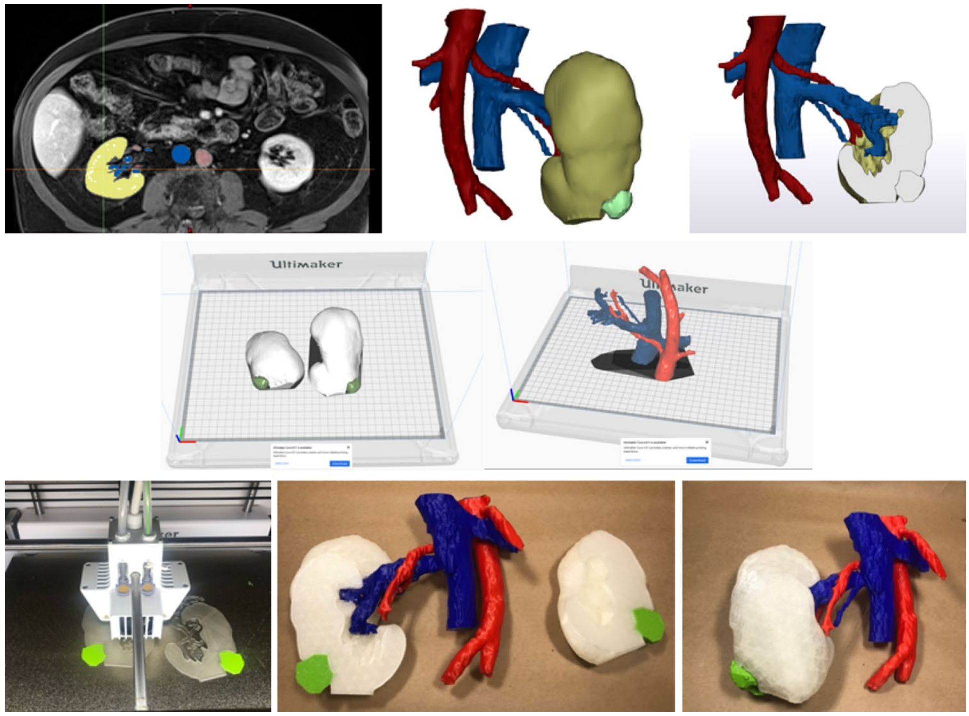

Fig. 1 **A** Axial CT cut used for segmentation. **B** Virtual 3D rendered CT image in Materialize Mimics. **C** Virtual 3D kidney sliced along longitudinal axis. **D**, **E** Model being prepared for printing in Ultimaker Cura software. **F** Model being printed. **G** The model's two pieces. **H** Model with pieces together

resident, and often a fellow. The first survey was completed before seeing the model and consisted of five multiple choice questions adapted from the Wake et al. [8] regarding operative plan (open vs robotic, transperitoneal vs retroperitoneal, clamping of vessels) followed by a sixth question performed on a 10-point visual analog scale ranking their confidence in their answers. The second survey was completed after seeing the model but before surgery and repeated the same questions. The third survey was completed after surgery and had questions regarding the utility of the model during the surgery (Online Appendix 2).

Surgical technique

All RAPN were performed by one of six attending surgeons using a Da Vinci surgical system® (Intuitive Surgical, Sunnyvale, CA) via a transperitoneal or retroperitoneal approach. Port placement was the same for each case based on the approach, i.e., transperitoneal versus retroperitoneal. Intraoperative ultrasound was conducted using the robotic drop in transducer probe 8826 (made by BK Medical).

Arterial clamping was performed in all cases using bulldog clips (made by Aesculap). Renal vein clamping was performed in some cases as well. Indocyanine Green was given (one vial was reconstituted with 10 ml of sterile water and 4 ml given intravenously) just after arterial clamping and perfusion to the kidney and tumor was assessed with Firefly feature of the Da Vinci surgical system based on surgeon preference.

After mass excision, a standard two-layer renorrhaphy, was completed with a 3-0 V-Loc® on the medulla and simple interrupted 0-vicryl sutures on a CT-1 needle on the coretex using sliding clip technique. Hemostatic product was used at surgeon discretion.

Statistical analysis

Data were expressed as means and standard deviations (SDS) for continuous variables. Statistical comparisons between survey responses of the same individual were performed using paired one-sided *t* tests.

Retrospective chart review was performed of patients without 3D modeling who underwent robotic partial nephrectomies at TJUH between 2018 and 2020 to act as controls. Patients with individualized 3D models were matched with the controls using One-to-One Matching prioritizing matched variables by (1) nephrometry score, (2) demographics (sex, age, race, and BMI), (3) operative technique, and (4) affected kidney. Analysis was performed to determine if variables between groups were similar. Pre-operative labs, intraoperative data, and post-operative labs and complications were compared between patients with individualized 3D models and historical controls using two-sample one-sided *t* tests.

Results

Patients

The cohort of patients undergoing 3D models consisted of 40 patients of which 38 filled out all questionnaires. There were 26 men and 14 women with a median age of 62.5 years (range from 29 to 78). The average nephrometry score was 7.4 (4–11). 33 patients had surgery via a transperitoneal approach while 7 patients had a retroperitoneal approach. There were no conversions to open surgery and there were three conversions to radical nephrectomy. In one the patient elected for radical before surgery, one was assessed before surgery to be likely, and the third was determined during surgery. Pre-operative, patient demographics, tumor characteristics, operative and peri-operative data are described in Table 1. All patients were insured.

Patient response to model

For all four questions regarding their anatomy and surgery, patients reported having statistically significantly higher understanding after viewing their individualized model ($P < 0.001$) as shown in Fig. 2. The patients had an average of a 2.7 point increase towards full understanding of the kidney itself (5.0–7.7 out of 10), a 2.4 increase in understanding of their disease, a 2.0 increase in understanding of the surgery and a 2.6 increase in understanding of the risks and complications related to surgery as ranked out of 10 on the visual analog scale.

Trainee responses to model

Residents completed surveys for 34 out of the 40 cases. The fellow completed surveys for 32 of the cases.

Table 1 Clinical characteristics of the study sample and peri-operative and oncological outcomes

Variable	Median (range)
Age (years)	62.5 (29–78)
Male/female	26/14
BMI (kg/m^2)	28.7 (19.9–40.4)
Right-/left-sided	22/18
R.E.N.A.L nephrometry score	7 (4–11)
Operative time (min)	195 (97–334)
Warm ischemia time (min)	25 (3–44)
Estimated blood loss (ml)	75 (20–250)
Transfusions	0
Conversion to radical nephrectomy	3

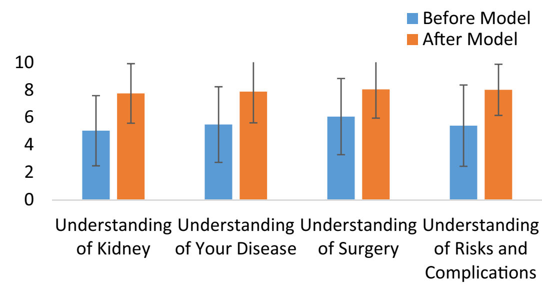

Fig. 2 Patient understanding before and after seeing the 3D model

The residents and fellow demonstrated a statistically significant increase in their confidence regarding the planned surgical approach after viewing the model based on responses to the pre- and post-model surveys ($P < 0.001$) as shown in Fig. 3. The residents' confidence increased by 0.71 and the fellow's by 0.97 points.

The average score for how much the model helped with understanding of comprehension of anatomy and surgical planning was 7.2 out of 10 for the residents and 6.6 for the fellow. The amount the model increased the residents' and fellow's confidence the surgery was planned correctly was on average 6.7 and 6.5 out of 10, respectively.

Attending response to model

The Attending surgeon also filled out the surveys and there was a small increase in confidence (0.44 points) after viewing the model that reached statistical significance ($P = 0.008$). In the third survey, the average score was 7.8 for the model's help in understanding of comprehension of anatomy and surgical planning. The average score was 7.6 for the model increasing confidence that the surgery was planned correctly. There were three surgeries in which the attending's plan of approach changed after viewing the model. Attendings changed their planned approach (transperitoneal versus retroperitoneal) four times and their vascular clamping decision four times. In one case, the pre-operative plan for

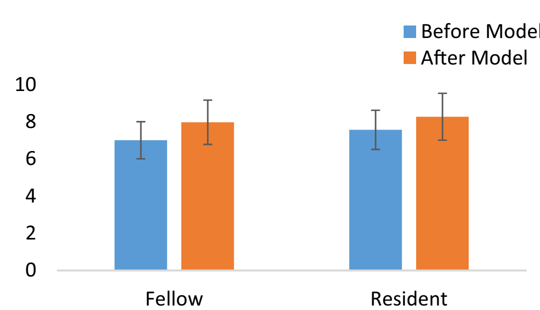

Fig. 3 Fellow and resident confidence in planned surgical technique before and after seeing the 3D model

the extent of vascular clamping was changed during surgery from "artery and vein" to "all arteries."

Comparison of surgical data in historical controls

Patient age, BMI, and nephrometry score were not statistically significantly different between the two groups. Patients with 3D modeling had shorter warm ischemia time, shorter length of operation, less intraoperative blood loss, and shorter length of stay (Table 2). In comparison to pre- and post-operative labs, there was less change in creatinine and hemoglobin. The length of hospital stays and change in creatinine were statistically significant.

Discussion

3D printing has gained popularity over the last decade due to reduced costs and faster fabrication. While there has been more pervasive use in some surgical fields such as orthopedics, the role in urologic surgery is still being defined [1, 4, 6]. A study by Gill et al. showed that 3D printing had a high utility in the planning for partial nephrectomy as well as a high concordance between 3D-printed models and the histological specimen [13]. However, while 3D models have been shown to be useful in operative planning, these models are prohibitively expensive for everyday practice and there has not been robust data to determine their utility in education of the patient and trainees.

During a 9-month period, we created 40 3D models for patients with kidney tumors determined amenable to partial nephrectomy. Our 3D models were inexpensively created with a commercially available 3D printer and contained the relevant anatomy for performing a RAPN. To study its effectiveness, we employed surveys with a well-established scoring system in this field [5, 14].

Our study showed the 3D model was associated withsignificant improvements in all domains tested: level ofpatient's understanding of the kidney itself, their disease,and the surgery they were to undergo, including its potentialcomplications. We feel this was the most noteworthy use ofthe 3D models. In addition, our patients routinely verbalizedthat they had a better understanding of their disease andthe surgery after interacting with their model. The modelappeared to enhance the communication between the patientand the surgical team, an important variable not capturedby the survey. Others have documented a similar positiveinfluence on patient satisfaction [1]. It stands to reason thatthe model allowed the patient to have a better understandingof their illness and the surgery to address it. This means itimproves a patient's health literacy which per the CDC isdefined as "an individual's ability to find, understand and useinformation and services to inform health related decisionsand actions for themselves and others." Health literacy playsan important role in the quality of healthcare delivery, andit has been shown patients with better health literacy havebetter outcomes [15].

We also demonstrated that the model is associated with an improvement in trainee understanding of the surgery. This is notable as competing resources, increased costs, and the evolving academic environment has resulted in challenges for programs training residents in robotics [7]. RAPN has a steep learning curve which amplifies the challenges of training urologic residents [16]. Therefore, tools that may expedite learning are increasingly important. Some have gone a step further with 3D models to practice RAPN on the model itself. While this has been shown to be beneficial, it is currently an expensive proposition with limitations [9].

Our study suggests that 3D models help trainees understand renal anatomy and the surgical approach which in turn may result in more effective teaching. The models also resulted in effective changes in the trainee's planned approach to the surgeries. This endpoint may have been overlooked if the surveys were not employed; even if these decisions could certainly be confounded by informal discussions between the resident, fellow, and attending.

There was also a survey-measured effect on attending surgeons, including an improvement in confidence in surgical approach, as has been found in other studies [8]. Patients with 3D models had improved operative outcomes, including

Table 2 Comparison of operative outcomes between the patients with an individualized 3D model and patients without a 3D model

Variable	Patients with 3D model mean (SD)	Historical controls mean (SD)	*P* value
Warm ischemia time	23.6 (15.3–31.9)	26.6 (14.6–28.6)	0.11
Length of operation	199.8 (146.9–252.7)	201.7 (125–278.4)	0.45
Estimated blood loss	101.6 (18.7–184.5)	200.5 (−273.4 to 674)	0.11
Number of blood transfusions	0	2	
Number of complications	2	10	
Change in creatinine	0.1 (−0.07 to 0.3)	0.2 (−0.01 to 0.4)	**0.03**
Change in hemoglobin	1.56 (0.62–2.5)	1.6 (0.5–1.8)	0.35
Length of hospital stay	1.5 (0.6–2.4)	2.3 (1.1–3.5)	**0.0004**

Significant *P* values are given in bold ($P < 0.05$)

Table 3 Previous 3D model educational studies' cohort numbers, outcome(s) and cost

Study	Author	Number of models	Outcome measured	Cost (if given)
3D-printed renal cancer models derived from MRI data: application in pre-surgical planning	Wake et al.	10	Presurgical planning	$1000
Development and validation of 3D-printed virtual models for robot-assisted radical prostatectomy and partial nephrectomy: urologists' and patients' perception	Porpiglia et al.	10	Surgical planning, anatomical representation, role of technology	Not given
Individualized physical 3-dimensional kidney tumor models constructed from 3-dimensional printers result in improved trainee anatomic understanding	Knoedler et al.	6	Trainee nephrometry score accuracy on model vs CT	Not given
Measurement of the accuracy of 3D-printed medical models to be used for robot-assisted partial nephrectomy	Michiels et al.	16	Accuracy of 3D-printed model vs CT	Not given
Personalized 3D kidney model produced by rapid prototyping method and its usefulness in clinical applications	Lee et al.	10	Attending and student appraisal of model utility in understanding anatomy, pre-surgical planning and tumor localization	$650
Personalized 3D-printed model of kidney and tumor anatomy: a useful tool for patient education	Bernhard et al.	7	Assessment of patient knowledge regarding kidney physiology, kidney anatomy, tumor characteristics and surgical procedure before and after seeing their 3D model	$560
Physical models of renal malignancies using standard cross-sectional imaging and 3-dimensional printers: a pilot study	Silberstein et al.	5	Pilot study	Not given
Usefulness of personalized three-dimensional printed model on the satisfaction of pre-operative education for patients undergoing robot-assisted partial nephrectomy and their families	Teishima et al.	29	Patient questionnaire related to kidney anatomy, tumor related issues and surgical issues after viewing model	Not given
Utility of patient-specific silicone renal models for planning and rehearsal of complex tumor resections prior to robot-assisted laparoscopic partial nephrectomy	Carl von Rundstedt et al.	10	Assessment of pre-operative rehearsal of tumor resection vs RAPN and assessment of model accuracy	Not given
Utilization of a three-dimensional printed kidney model for favorable TRIFECTA achievement in early experience of robot-assisted partial nephrectomy	Fujisaki et al.	50	Retrospective assessment of model's impact on TRIFECTA achievement (negative margin, warm ischemia time < 25 min, absence of peri-operative complications)	$10
3D-printed soft-tissue physical models of renal malignancies for individualized surgical simulation: a feasibility study	Maddox et al.	7	Comparison of clinical outcomes in patients undergoing RAPN with prior model rehearsal vs matched controls	"Significant cost"
Development and validity of a silicone renal tumor model for robotic partial nephrectomy training	Monda et al.	4	Face, content, and construct validity of the models as training tools in simulations	$260

number of transfusions and number of complications. There was a relative decrease in time-sensitive factors such as length of operation and warm ischemia time, with a significant decrease in length of stay. Enhanced understanding of the tumor and kidney anatomy and increased discussion on the plan between the surgical team pre-operatively may also have contributed to this. This suggests that incorporating a model into standard workflow for patients receiving RAPN may shorten patient stay and improve patient outcomes.

A goal of this study was to determine the utility of an inexpensive but detailed kidney model in trainee and patient education. Other studies have utilized models that were more expensive or labor-intensive to produce (Table 3). Based on our experience, our next step will be to consider utilization of 3D printing in surgical planning with more advanced kidney tumors or with surgery specific to other organs, such as the adrenal gland. Going forward, we envision 3D models will continue to serve as an established pre-operative tool for other urologists.

This study is not without limitations. A goal of the project is to determine if a pragmatic process for 3D model creation can be used. While the models were inexpensive and rapidly printed, the interpretation of the imaging and subsequent segmentation required a radiologist and trained printing technician. While there was no additional cost for this labor during the study, when used in practice the design lab charges $200 to perform the segmentation and $40 for processing, for a total cost of $270–290 per model. The price of this work will vary by institution based on who is performing the segmentation and processing. Although it is reasonable to assume in the future that a urologist can work with the printing technician, the technology is not yet at the point where the process can be performed without a technician. This is because computer algorithms are not yet advanced enough to control the 3D printer based on simply identifying the target lesion on both CT and MRI imaging. In addition, more plainly, the printed vasculature had to be glued to the model by hand, a process requiring completion by the technician. The need to hire additional personnel to perform these functions will depend how many cases are performed per week and the ability of existing staff to take additional roles.

Survey results may have been affected by bias and additional time spent with patients. Since the attendings, residents, and fellow in this study were all staff at the institution administering the survey, there may have been a more favorable response to the models. Multiple attendings and residents were surveyed to account for some individual bias. While the amount of time spent with the patient was not measured in this study, because the model was shown to the patient on the morning of surgery, the amount of available time for the surgeon to explain the procedure to the patient pre-operatively was equally limited. However, if the 3D model did force the team to spend more time with the patients to increase the patient understanding, then the model is still benefitting patients in that it encourages more of these patient education interactions between patients and providers.

We were unable to capture the educational background and employment history of our patients, which may have affected their understanding of their disease and the models. Finally, our comparison group was from retrospectively collected data, and has the inherent biases of such analyses.

Conclusions

In conclusion, our study shows that individualized yet inexpensive 3D models have a significantly positive impact on patient health literacy and on improved trainee understanding of renal anatomy and confidence in the surgical approach. Further studies will evaluate more advanced renal tumors and 3D models for surgical planning in other urologic organs.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11701-022-01441-6.

Author contributions CDL: conceptualization, writing (review and editing), and supervision. ERS: methodology, investigation, data curation, formal analysis, and writing (original draft, review and editing). AS and AMQ: investigation, data curation formal analysis, and writing (original draft, review and editing). RP: resources, methodology, and supervision. SM, AK, KB, and MH: methodology. TC, MM, EJT, and VD: supervision. AS, CM, AD, AS, and CBC: data curation.

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Declarations

Conflict of interest The authors E. Reilly Scott, Abhay Singh, Andrea M Quinn, Samuel Morano, Alice Karp, Kaitlyn Boyd, Michelle Ho, Adam Schneider, Connor McPartland, Andrew Denisenko, Andrew Shumaker, Cassra B. Clark, Thenappan Chandrasekar, Mark Mann, Edouard J. Trabulsi, Vishal Desai, Robert Pugliese, and Costas D. Lallas declare that they have no conflict of interest.

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