Laparoscopy and Robotics

The Use of 3-Dimensional, Virtual Reality Models for Surgical Planning of Robotic Partial Nephrectomy

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OBJECTIVE	To determine whether 3-dimensional virtual reality models of patient-specific anatomy improve outcomes in patients undergoing robotic partial nephrectomy.
MATERIALS AND METHODS	Computed tomography and magnetic resonance imaging scans for 30 patients undergoing robotic partial nephrectomy were converted to 3-dimensional virtual reality models prior to the patient's operation. These models were then viewed on the surgeon's mobile phone pre- and intraoperatively using a Google Cardboard headset to assist in surgical planning. This group was compared to 30 patients who previously underwent robotic partial nephrectomy. We compared operative time, clamp time, estimated blood loss, hospital stay, complications, and margin status between these groups. We used forward selecting multivariate regression models to create the final model controlling for significant demographic and clinical variables.
RESULTS	When controlling for case complexity and surgeon, patients with 3-dimensional, virtual reality-assisted surgical planning had significantly lower operative time (141 minutes vs 201 minutes, $P < .0001$), clamp time (13.2 minutes vs 17.4 minutes, $P = .0274$), and estimated blood loss (134 cc vs 259 cc, $P = .0233$). Patients without 3-dimensional, virtual reality-assisted surgical planning were more likely to have a hospital stay of greater than 2 days (odds ratio 5.1, 95% confidence interval 1.0, 26.4). There were no complications or positive margins noted in the VR group.
CONCLUSION	Use of a 3-dimensional, virtual reality model when performing robotic partial nephrectomy improves key surgical outcome parameters. UROLOGY 125: 92−97, 2019. © 2019 Elsevier Inc.

Surgical planning for such complex operations has, since the advent of the computed tomography (CT) in the 1970s, been predominately based on review of 2-dimensional (2D) images sequentially complied in a dataset and reviewed by the surgeon in rapid succession. By performing this function, surgeons mentally construct a 3-dimensional (3D) model that is their singular guide to simulate the patient's anatomy. Although repetition over the course of the surgeon's career lends a certain comfort and familiarity with this technique, it is unclear if this mental image fully simulates the actual anatomy of the patient.

While imaging technology has improved since the advent of the CT scan, the method of presentation to the viewer has remained largely the same. In the era of ultrahigh definition displays, mobile data access through smartphones, cloud-based computing, and virtual reality (VR), image visualization for surgical planning remains 2D, console based, and standard definition. Although this is the accepted standard for preoperative planning, the emergence of rapidly advancing technology in these other arenas suggest areas prime for accelerated growth and improvement. In particular, the 3D, interactive nature of VR and the ability to better demonstrate the anatomy pertinent to operations has been identified as a key area from which surgeons may derive outsize benefits.

Collectively, this suggests that areas within surgical planning are ripe for renovation in conjunction with new technology. Accordingly, we identified robotic partial nephrectomy as an index, standard of care, robotic surgical case involving a solid organ, and tumor resection.[1-5] We then sought to determine if the use of a 3D image processing and VR viewing system would augment the surgical planning process and result in improved patient outcomes.

MATERIALS AND METHODS

Data Source and Participant Eligibility

All participants were treated at a large academic medical center, and this study was approved under an Institutional Review Board Quality Improvement exemption. Patients undergoing a bilateral operation, with greater than 2 renal masses, or without a preoperative CT or magnetic resonance imaging (MRI) with contrast were excluded from the study groups. The intervention group included patients who were scheduled to undergo robotic-assisted laparoscopic partial nephrectomy, identified from the operating room schedule. Patients were accrued in chronological order for a total of 30 cases. The control group was identified from the surgical schedule as patients having undergone robotic-assisted laparoscopic partial nephrectomy starting 6 months prior to the intervention implementation and continued in chronological order until 30 eligible cases had been identified. This period was utilized to homogenize the level of training of the residents and fellows involved in the cases. All operations were performed by 3 attending surgeons who were beyond their learning curve, having completed 250+ of these operations.[6]

Demographic data were collected for both groups from the medical record, including age, sex, race, employment status, and relationship status. Clinical data collected included surgeon, resident, or fellow involvement in the surgery, mass size, R.E.N.A.L nephrometry score, laterality of operation, and t-stage. Nephrometry score has been validated and was utilized as a measure of case complexity and a predictor of perioperative outcomes for patients undergoing robotic partial nephrectomy.[7,8] We identified outcome measures of interest from recent literature comparing robotic and laparoscopic partial nephrectomy.[9,10] Our primary outcome measure, operative (OR) time, and secondary outcome measures, clamp time (warm ischemia time), estimated blood loss (EBL), and hospital stay, were collected from the medical record.

CT and MRI scans for patients in the intervention cohort were converted to deidentified 3D virtual reality models prior to the patient's operation. This multistep process was developed prior to the initiation of this study and involves the extraction of individual voxels from the CT scan to form 3D structures, postprocessing modifications to separately identify and colorize the renal artery, renal vein, kidney parenchyma, collecting system, and tumor(s), and upload to a VR viewer. The kidney body was rendered semitransparent to aid with identification of mass location, depth, and proximity to the other structures (Fig. 1). Models were loaded onto the surgeon's mobile phone using a web-based application. They were then viewed by the surgeons preoperatively using a Google Cardboard headset (Fig. 1). This inexpensive (around 15 dollars) headset allowed the surgeon to see the model in VR, virtually orbit around the model by turning their head or looking up and down, and zoom in and out on specific parts of the anatomy using a small button on the top of the headset. Surgeons continued to view the source CT or MRI scan as part of the preoperative planning process as well. For the control group, surgeons viewed only CT or MRI imaging as part of the preoperative planning process.

Data Analysis

Sample size was calculated so that the study would have 80% power to detect a 15% difference in mean operating room time between intervention and control groups using a 2-tailed t test at an alpha level of 0.05. We performed a natural log transformation of OR time, clamp time, and EBL to achieve normal
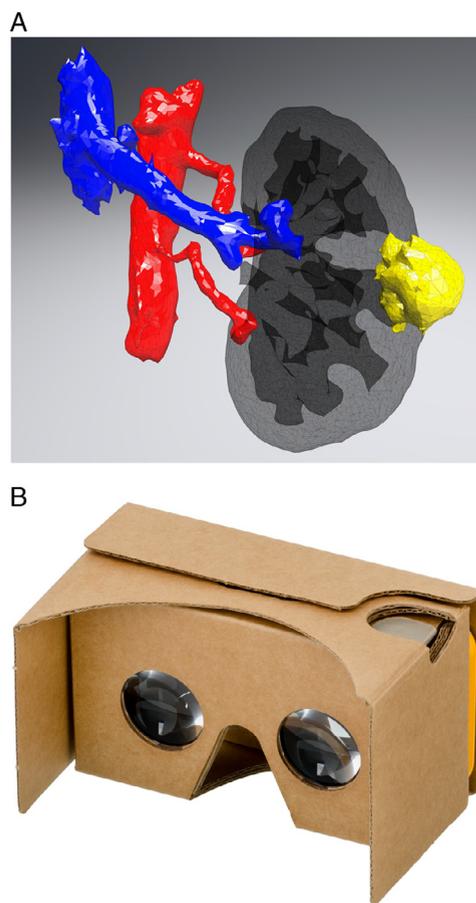
Figure 1. **(A)** 3D model of left kidney with lower pole accessory renal artery interpolar mass. **(B)** Google Cardboard headset with phone. (Color version available online.)

distribution. We also dichotomized untransformed OR time, clamp time, and EBL at above (high) vs at or below the 75th percentile for each outcome (low) for the total cohort, which correlated with the clinically relevant cut points outlined below. Finally, we dichotomized hospital stay at 0-2 (low) days vs >2 days (high), as this represented the natural cutpoint for acceptable length of stay at our institution.

As an initial analytical step, we compared baseline characteristics between cases performed with (intervention) or without (control) 3D virtual reality models. Next, we used a nonparametric test to compare medians (Wilcoxson rank sum test) of the untransformed OR time, clamp time (among those with clamp time >0), and EBL, t tests for the log-transformed OR time, clamp time, and EBL, and Chi-square tests for high vs low dichotomized outcome variables. Finally, for the multivariate analyses, we conducted linear regression on the log-transformed OR time, clamp time, and EBL. The adjusted means and 95% confidence interval were back-transformed (with a correction with the bias factor of $e^{MSE/2}$) into the native units. We conducted a logistic regression for length of stay, with intervention as the referent group. For all 4 models, we included nephrometry score and surgeon, and conducted a forward selection process, resulting in the final model controlling for significant demographic and clinical variables. All statistical tests were 2-sided and carried out at the 5% significance level, using SAS 9.4 (Cary, NC).

Table 1. Patient demographic and clinical characteristics (N = 60)

	Virtual Reality (n = 30)	No Virtual Reality (n = 30)	P
Age, mean (SD)	63.4 (13.0)	60.9 (15.0)	.4866
Sex			
Male	63% (19)	40% (12)	.0705
Female	37% (11)	60% (18)	
Race			
White	70% (21)	83% (25)	.2221
Non-white	30% (9)	17% (5)	
Relationship status			
In a relationship	63% (19)	67% (20)	.7866
Not in a relationship	37% 911)	33% (10)	
Employment status			
Full or part-time	70% (12)	37% (11)	.2767
Unemployed	23% (7)	10% (3)	
Unknown	37% (11)	53% (16)	
T stage			
T1/T2	50% (15)	60% (18)	.3807
T3	23% (7)	10% (3)	
Tx	27% (8)	30% (9)	
Mass size			
Mean (SD)	3.74 (2.17)	2.95 (1.86)	.1613[a]
Median (IQR)	3.35 (1.70-5.00)	2.50 (1.60-63.20)	.1714[b]
Nephrometry Score			
4	3% (1)	33% (9)	.0004[c]
5	3% (1)	15% (4)	
6	7% (2)	15% (4)	
7	13% (4)	26% (7)	
8	23% (7)	11% (3)	
9	13% (4)	0% (0)	
10	17% (5)	0% (0)	
11	3% (1)	0% (0)	
12	3% (1)	0% (0)	
Multiple masses	13% (4)	0% (2)	
Surgeon			
Surgeon 1	57% (17)	63% (19)	.9309[c]
Surgeon 2	30% (9)	23% (7)	
Surgeon 3	13% (4)	13% (4)	
Fellow, % yes (n)	73% (22)	73% (22)	.9999
Resident, % yes (n)	97% (29)	87% (26)	.3533[c]
Laterality			
Right	43% (13)	50% (15)	.6048
Left	57% (17)	50% (15)	

[a] Wilcoxon rank-sum test of means.
[b] Brown-mood test of medians.
[c] Fisher's exact test.

RESULTS

There was a significant difference in the complexity of cases between the intervention and control groups as defined by nephrometry score, with the intervention group having more complex cases (P = .0004) (Table 1). The complexity of cases in the intervention group increased as the study progressed (nephrometry score mean 8.4 for first 15 cases vs 9.3 for second 15) (data not shown). There were no other differences in baseline characteristics noted between groups. Of note, intraoperative ultrasound was used for all cases (data not shown). Unadjusted medians and log-transformed means for all primary outcomes trended lower in the intervention group, but there were no significant differences between the groups before controlling for case complexity (Table 2).

After controlling for case complexity and surgeon, patients with VR-assisted surgical planning had significantly lower OR time (141 minutes vs 201 minutes, P < .0001), clamp time (13.2 minutes vs 17.4 minutes, P = .0274), and EBL (134 cc vs 259 cc,

P = .0233) (Table 3). Patients without VR-assisted planning were more likely to have a hospital stay greater than 2 days (odds ratio 5.1, 95% confidence interval 1.0, 26.4) (Table 3). There were no cases with either complications or positive margins in the intervention group. There were 2 complications (1 bowel injury and 1 vascular injury) and 3 positive margins in the control group.

DISCUSSION

Over the past decade, care for solid organ cancers has been revolutionized by rapid advances in surgical technology, including robotic surgery. This has led to a parallel acceleration in minimally invasive surgeries, owing in part to the decrease in the overall difficulty of this approach when performed with robotic assistance.[11] We identified robotic partial nephrectomy as an index case for solid

Table 2. Comparing outcomes between groups with and without virtual reality

	Virtual Reality (n = 30)	No Virtual Reality (n = 30)	P
OR time (mins)			
Median (IQR)	175 (128, 197)	185 (164, 228)	.1789[c]
Mean (SD)[a]	166 (157, 175)	188 (177, 199)	.1162[d]
>75th percentile, % (n)[b]	20% (6)	30% (9)	.3711[e]
Clamp time (mins)			
% any	79% (23)	76% (22)	.7529[e]
Median (IQR)	12.5 (10, 16)	15 (10, 19)	.5866[c]
Mean (SD)[a]	12.8 (11.9, 13.9)	13.7 (12.7, 14.8)	.5495[d]
>75th percentile, % (n)[b]	20% (6)	30% (9)	.3711[e]
EBL (cc)			
Median (IQR)	125 (50, 300)	150 (100, 250)	.7000[c]
Mean (SD)[a]	135 (112, 162)	150 (127, 177)	.6672[d]
>75th percentile, % (n)[b]	23% (7)	13% (4)	.3169[e]
Length of stay >2 days, % (n)	53% (16)	73% (22)	.1080[d]
Complications, % (n)	0% (0)	7% (2)	.4915[f]
Margins, % (n)	0% (0)	10% (3)	.1124[f]

[a] Back transformed from natural log scale.
[b] 75th percentile: OR time = 222 minutes, clamp time = 17 minutes, EBL = 300 cc.
[c] Wilcoxon rank-sum test of medians.
[d] t test of means.
[e] Chi-square test of proportions.
[f] Fisher's exact test.

Table 3. Adjusted means from multivariate regression

	Virtual Reality	No Virtual Reality	P
OR time[a]	141 (120, 165)	201 (174, 232)	<.0001
Clamp time[b]	13.2 (11.5, 15.2)	17.4 (14.9, 20.3)	.0274
EBL[c]	133 (92, 193)	259 (174, 386)	.0233
LOS (>2 vs 0-2 days)[d]	——	5.1 (1.0, 26.4)	.0498

[a] Back transformed from linear regression controlling for nephrometry score, surgeon and resident.
[b] Back transformed from linear regression controlling for nephrometry score and surgeon.
[c] Back transformed from linear regression controlling for nephrometry score and surgeon.
[d] Odds ratio from logistic regression controlling for nephrometry score and surgeon.

organ resection owing to the characteristics of the case that are replicated in other similar cases. As such, planning for this surgery, which relies on precise identification of the renal vasculature, identification of tumor location and depth, and avoidance of surrounding structures, remains difficult when relying on traditional, 2-dimensional CT imaging. Previous efforts to improve surgical planning for partial nephrectomy include the review of 3D printed models as part of the preoperative planning process.[12-15] These studies were mostly feasibility studies, although few did demonstrate improvement in outcomes within specific patient populations.[13] The drawbacks to 3D printing models for surgical planning are substantial, including cost and lack of fidelity, and preclude use at scale. In this setting, our study has several important findings.

For patients undergoing robotic partial nephrectomy, we found that key metrics that define a successful surgery improved across the board, after controlling for case complexity and surgeon. To our knowledge, this is the first demonstration of the benefit of point of care, 3D VR imaging for surgical planning. While our baseline cohort's outcomes compare favorably with published data for these outcomes, those observed in the intervention group represent a significant clinical improvement over previously published data.[10] Furthermore, there were significantly more complex cases in the intervention group when compared to the control. In fact, the complexity of cases increased as the study progressed. This increase in case complexity may be explained by subjective surgeon comments during the study. Several surgeons reported that an increased confidence in preoperative planning using the 3D VR models allowed them to undertake cases that historically had associated poorer outcomes due to the degree of difficulty.[16] Other changes in the preoperative planning process reported by the surgeons included changing the case type from a radical nephrectomy to a partial nephrectomy, modifying approach for posterior masses, and selective vascular clamping.

When assessing the complications in the control group, it is likely that the vascular injury could have been prevented by the VR model, as the vasculature is shown in detail and aids in the hilum dissection. The colonic injury likely would not have been prevented by the VR model. These cases were slightly longer than the mean when controlled for complexity, but when we excluded these 2 cases from the analysis, there was no appreciable difference in the overall results of the study. Regarding the 3

positive margins in the control group, we hypothesize that seeing the tumor depth in 3D was an adjunct to the intraoperative ultrasound that allowed surgeons to more confidently attain negative margins. This is consistent with some of the nonsurvey feedback we received from the surgeons using the VR models. Specifically, surgeons suggested that seeing clear delineation of the depth of tumor in relation to other landmarks such as the sinus fat and collecting system provided a better roadmap for resection depth.

The improvements we demonstrate from the use of this technology can be attributed to the science behind the system the human brain uses to process visual information. Approximately 50% of the human brain is dedicated to visual image processing, but without certain depth cues, its visual perception is not reliable.[17] Even with the assistance of 3D computer modeling, the complex data patterns required to display 3D objects on 2D screens are still unable to provide spatial relationships or depth information in a way that allows correct visual interpretation.[18] When constructing mental 3D images from 2D, the brain relies on 5 psychological depth cues: linear perspective, occlusion (the obscuration of a more distal object by a more proximal object), shading, texture, and prior knowledge of familiar sizes and the shapes of common structures.[19] Linear perspective, or the relative distance among objects in a series of CT images, and prior knowledge, the presumption of how certain structure in the CT image "should" appear, in particular introduce a tremendous amount of bias into the mental anatomic image formed by the surgeon. These cognitive processing biases can result in less accurate estimation of tumor and blood vessel size and relative location, which in turn can affect overall OR time, blood loss, clamp time, and downstream outcomes.

True 3D sensation relies on separate visual cues: accommodation, convergence, motion parallax (a monocular depth cue in which objects that are closer are viewed as moving faster than objects that are further away), and binocular disparity.[20] These cues have been strategically targeted by designers of head-worn 3D displays since their inception to fully simulate the natural visual environment.[21] Newer headsets and high-resolution displays such as those used in this study incorporate technologies that utilize these cues. Though a detailed description of these factors is well beyond the scope of this study, they give the viewer a full 3D experience (hence the term, "virtual reality"). Thus, the viewer sees an image that appropriately simulates the patient's anatomy in a way that the brain can easily perceive, without the inherent bias that mental 2D to 3D conversion introduces. We believe that by this mechanism, better preoperative planning can be achieved, leading to better surgical outcomes.

Our study has several limitations. First, issues have been raised with the reliability and predictive value of nephrometry scores. However, nephrometry scores have been reliably used to stratify the complexity of cases, and higher nephrometry scores have previously been associated with greater blood loss, warm ischemia time, overall operative time, and length of stay >2.2 days.[11] Furthermore, the scoring system is remarkably easy to use, with very little variation in the interpretation of images.[8,22] Second, the control group used in this study is retrospective, while the intervention group is prospective. While this may introduce bias, we were careful to ensure that surgical equipment, personnel, and technique remained constant between the groups. The period from which the control group was derived was specifically defined to ensure the same ancillary and trainee staff was present for all cases between groups. The level of participation of the trainee was also standardized as much as possible between groups. Third, the fact that the surgeons were aware that they were being timed and their outcomes recorded during the prospective deployment of the intervention means that bias may be introduced into the study via the Hawthorne effect. This could potentially impact operative times due to the surgeon operating faster in intervention cases, or blood loss, which is surgeon reported. To mitigate the risk for bias in these areas, we used operative times that were documented by the nursing staff in the medical record as part of standard OR procedure, and blood loss figures that were agreed upon postoperatively by the surgeon and the anesthesia staff. Clamp time and length of stay were taken directly from the medical record and likely would remain unaffected by this type of bias. Finally, these results are taken from 1 academic setting, and may not be generalizable to other institutions.

These findings can impact care in several ways. We anticipate this technology may affect care at the patient, physician, and hospital level. At the patient level, the benefits of the decrease in our primary outcome measures are both intuitive and supported by myriad research. Longer operative times and increased blood loss have been associated with increased 30-day perioperative complications for a variety of operations, including robotic partial nephrectomy.[23-25] Limiting nephron loss due to hypoxia can be accomplished by both keeping overall clamp time as low as possible and by selective clamping, both facilitated by this imaging.[26] Finally, early hospital discharge limits the probability of a hospital-acquired condition, and has been shown to be effective in this regard for patients undergoing robotic partial nephrectomy.[27,28]

The surgeon is the key operator in determining whether the patient derives benefit from the use of this technology, and as such the benefits to both are inextricably linked. To enhance treatment delivery in these patients at a population level, further work should focus on ways to integrate these models with the surgeon's preoperative planning process. Integration with tools that are used regularly in the operating room, like the surgical robot, and ensuring that viewing is streamlined within the normal flow of the case, will be crucial in facilitating the improvement of outcomes using this tool. While we studied the use of 3D VR imaging in the setting of small renal masses, this technology could offer similar benefits to patients

undergoing surgery for a variety of other conditions, though this remains to be tested.

CONCLUSION

In patients undergoing robotic partial nephrectomy, using 3D VR models for operative planning improved key parameters that can impact outcomes, providing benefit at the patient, physician, and hospital level. Further work should seek to replicate these findings in larger randomized controlled trials, test methods of integration into the surgical workflow, and investigate the impact of use in other complex case types.

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