Original Article

Holographic reconstruction technology used for intraoperative real-time navigation in robot-assisted partial nephrectomy in patients with renal tumors: a single center study

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Background: To explore the efficacy and advantages of real-time navigation using holographic reconstruction (HR) technology combined with da VinciTM robotic system for partial nephrectomy (PN) in patients with renal tumor.

Methods: The clinical data of 41 patients with totally intrarenal tumors receiving robot-assisted partial nephrectomy (RAPN) from April 2018 to October 2020 in our department were collected and retrospectively analyzed. All operations were performed by the same surgeon. HR technology and three-dimensional (3D) reconstruction techniques were applied for real-time navigation to resect tumors using the da VinciTM robotic system. The relevant clinical parameters and surgical outcomes of the patients were recorded and analyzed.

Results: HR technology allowed accurate evaluation of tumors, renal hilus vessels, and surrounding organs during the operation. With real-time navigation HR, all cases were performed by RAPN. The mean operative time was 115.3±20.3 (range, 70–153) minutes, and the warm ischemia time (WIT) was 18.7±3.9 (range, 13–28) minutes. The estimated blood loss (EBL) was 98.8±18.7 (range, 60–141) mL. Negative surgical margins were reported in all cases. Patients with absence of grade ≤1 Clavien-Dindo complications. Compared with the clinical outcomes of standard RAPN, as reported in the literature, HR-assisted technology reduced the mean operative time, the WIT, and the EBL in patients undergoing RAPN. Therefore, combining HR with robotic abdominal surgery can enhance the efficiency of locating blood vessels and allow for more accurate resection of tumors.

Conclusions: As a novel and promising computer digital technology, HR can significantly improve the success of RAPN operations. This retrospective study demonstrated that HR-assisted operations resulted in shorter operation times and less perioperative complications and were thus safer and more effective in patients with renal tumors compared with RAPN not used HR.

Keywords: Holographic reconstructions (HRs); renal cell carcinoma; real-time navigation; robot-assisted partial nephrectomy (RAPN)

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Introduction

With advancements in medicine, partial nephrectomy (PN) has become a well-accepted standard for the nephron-sparing treatment of pT1 renal parenchymal tumors (1). Technological advances have fueled a paradigm shift from open surgery to minimally invasive techniques for PN (2). Indeed, minimally invasive approaches, including laparoscopic PN and more recently, robot-assisted (RA) procedures, have been increasingly accepted as a reliable surgical option for patients with small renal tumors, largely due to the refinement of surgical techniques and instruments (3,4).Compared with open nephron-sparing surgery (NSS), robot-assisted partial nephrectomy (RAPN) has achieved good results with accurate resection of tumors, protection of renal function, and prevention and control of perioperative complications (5-7). These advantages have resulted in a surge of robotic surgeries in hospitals.

The concepts of "precision medical treatment" and "precision surgery" have also attracted considerable attention. With continuous developments in the field of medical imaging, intraoperative guidance for the precise excision of tumors has become a new direction in laparoscopic surgery (8). Virtual reality technology uses computer simulation systems to generate three-dimensional (3D) dynamic images which integrate with entity behaviors and object interactions to create a "real scene" that allows user immersion and interaction. Holographic reconstructions (HRs) technology is a successful virtual reality technology that combines a full and immersive experience of three-dimensionality, interactivity, and versatility. Significantly, the realistic model allows the user to appreciate the detailed anatomy at a glance. The patient's computed tomography angiography (CTA) images are transformed into a holographic digital virtual organ to clearly display the internal kidney structures, providing real-time separation, interaction, measurements, and analytical functions. This assists doctors accurately identify and locate blood vessels, surrounding organs, and the target tumor, which facilitates planning of the operation mode and scope. Furthermore, robot operating systems allows a more magnified view and increased flexibility compared to the human arm. This renders the manipulations easier and safer.

In what was to our knowledge the first report that using the HR technology to navigated RAPN until now. This retrospective study analyzed the efficacy of HR in 41 patients with renal tumors who underwent RAPN with satisfactory results. Here we presented our preliminary experiences with this novel surgical navigation technique. Using this novel HR navigation system, the clinical outcomes of the surgery were significantly improved.

We present the following article in accordance with the STROBE reporting checklist (available at https://dx.doi.org/10.21037/tau-21-473).

Methods

Patients

A total of 41 consecutive patients with renal tumors who underwent RAPN in the Department of Urology Surgery, General Hospital of the Central Theater Command, Wuhan, China, between April 2018 to October 2020 were retrospectively included in this study. All operations were performed by the same experienced surgeon. Patient demographics, tumor characteristics, and preoperative clinical data are summarized in *Table 1*. All patients were preoperatively evaluated using an enhanced thin-slice CTA.

All procedures performed in this study involving human participants were in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by ethics board of General Hospital of Central Theater Command of the People's Liberation Army (Number: [2018]012) and informed consent was taken from all the patients.

HR technique

The HR software was produced by Renxin MedTech (Beijing China) and implemented on a NAVIGATOR workstation (Renxin MedTech) consisting of a Windows®-based computer with a stereoscopic screen to visualize objects in augmented reality. All patients underwent preoperative CTA examination. The CTA data were collated and saved in DICOM format, and uploaded to the NAVIGATOR workstation (*Figure 1A,1B*). Using the

Table 1 Patient demographics, tumor characteristics

Parameters	N (%)
Patient demographics	
Numbers	41
Ages, year [range]	60.1 [41–78]
Gender	
Male	27 (65.9)
Female	14 (34.1)
Body mass index, kg/m^2 [range]	24.7 [22.1–28.1]
Tumor characteristics	
Tumor site	
Right	22 (53.7)
Left	19 (46.3)
Tumor size, cm	
≤4	30 (73.2)
>4	11 (26.8)
R.E.N.A.L. score	
4–6	23 (56.1)
7–9	15 (36.6)
≥10	3 (7.3)
Location	
Hilar	13 (31.7)
Others	28 (68.3)
Solitary kidney	0 (0.0)

reconstruction and virtual image technology, the abdominal organs, the kidneys and their volume, the position and blood supply of the tumor, and other information can be accurately mapped and reconstructed. The reconstructed images and solid viscera can be mixed to achieve translucent, clear real-time navigation displays (*Figure 1C*).

Real-time navigation and surgical techniques

The whole workstation can be easily relocated to the operating room prior to surgery. The display of the HR workstation is synchronized with the TilePro multi-input display (Intuitive Surgical Inc., Sunnyvale, CA, USA). The HR renders and fuses the collected information into real-time abdominal contents. When the HR system is activated, two digital video interfaces will appear in the TilePro multi-input display, one is the real-time larger image displayed by the laparoscopic camera, the other is the interface of the HR integrated with the virtual reality technology for intraoperative real-time navigation (*Figure 2A*). The HR system is manipulated by the assistant surgeon to view specific anatomy. The anatomy model can be rotated, zoomed, hyalinized, obliterated, combined, or split to show organs, lesions, blood vessels, and anatomical relationships (*Figure 2B*).

After general anesthesia, the patient was placed in the lateral position, and the operation was performed through a transperitoneal approach. The laparoscopic camera was inserted into the abdominal cavity. The colon was dissociated to the midline, and the liver or spleen was further dissociated to completely expose the renal hilum area. With the HR navigation guidance of virtual reality fusion, the upper ureter, the renal artery, and the renal vein were dissociated, and the blood vessels were sequentially clamped using bulldog clamps. However, (17 out of 41 cases) The tumor was accurately located and second-dissociated (*Figure 3*), and the artery supplying the tumor was clamped by bulldog clips in a zero warm ischemia manner. The 360 panoramic view of the tumor, including the margin between the tumor and the renal parenchyma, is shown by HR in *Figure 4*. The renal parenchyma nearest to the tumor was selected for the incision, and the tumor was excised along the tumor bed in a reverse manner towards the normal renal parenchyma. In cases where the renal pedicle blood vessels were exposed or close to the renal hilum, the skirt suture or "C" suture method was used (13 out of 41 cases). The collecting system and the large vessels were closed with 3-0 V-Loc sutures, and renal parenchymal sutures using 2-0 V-Loc were then placed for cross-compression along the defect. The assistant inserted an entrapment bag and the tumor was extracted.

Statistical analysis

Continuous variables are shown as the mean and range. Categorical variables are shown as the frequency and percentage. All statistical analyses were performed using the SPSS 23.0 software (IBM Co., Armonk, NY, USA).

Results

The operation was successfully completed on all patients without conversion to open surgery or radical nephrectomy due to massive renal hemorrhage. Negative surgical

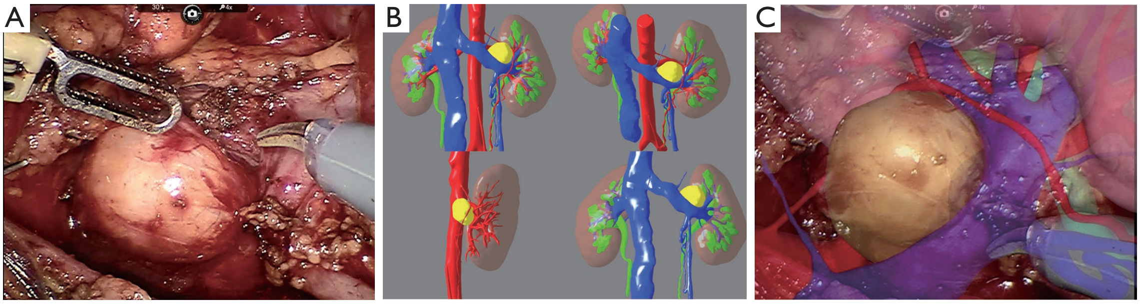

Figure 1 3D image reconstruction and mixed reality technology in HR. (A) The live renal tumor image was displayed by the laparoscopic camera; (B) the generate 3D dynamic image was generated by HR in same case; (C) mixed the live renal tumor image and 3D dynamic image to navigated the vessel and tumor margin unexposed. 3D, three-dimensional; HR, holographic reconstruction.

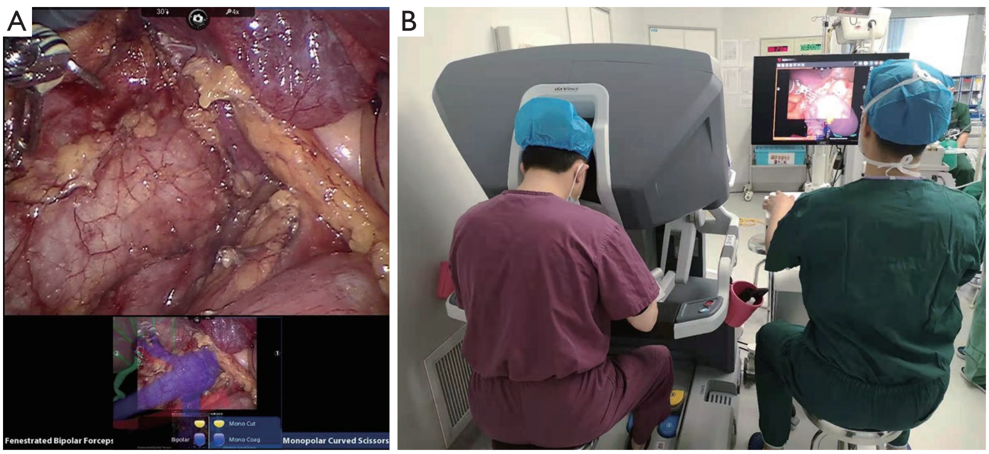

Figure 2 Mixed reality real-time navigation combine surgery technique. (A) The live image was displayed by the laparoscopic camera (large), the mixed reality real-time navigation image (small); two images were appeared in the TilePro multi-input display; (B) HR workstation is synchronized with the TilePro multi-input display the surgeon (dressed in red) manipulated the console, the assistant manipulated the HR workstation. HR, holographic reconstruction.

margins were reported in all cases. No patients required intraoperative or postoperative blood transfusions and none experienced severe complications (*Table 2*). The clinical characteristics for each patient including final pathology, margin status, and postoperative complications are listed in *Table 2*. Operation time, warm ischemia time (WIT), estimated blood loss (EBL), preoperative glomerular filtration rate (GFR), and postoperative renal GFR of the impacted kidney at the 3-month follow-up were collated (*Table 3*). There were a few postoperative complications including abdominal distention, unhealing wounds, and postoperative fever (Clavien classification I), all of which spontaneously subsided with symptomatic treatment. *Table 3* shows that the mean operative time was 115.3±20.3 (range, 70–153) minutes and the WIT was 18.7±3.9 (range, 13–28) minutes. The EBL was 98.8±18.7 (range, 60–141) mL. The estimated GFR decreased 16% from pre-operation to 3 months post-operation. Compared to standard RAPN reported in the literature (*Table 4*) (9-19), the implementation of HR with robotic abdominal surgery effectively reduced the operation time. Real-time intraoperative navigation enabled surgeons to easily identify the blood vessels of the renal hilum, thus avoiding damage to the blood vessels.

Discussion

A growing number of studies have demonstrated that

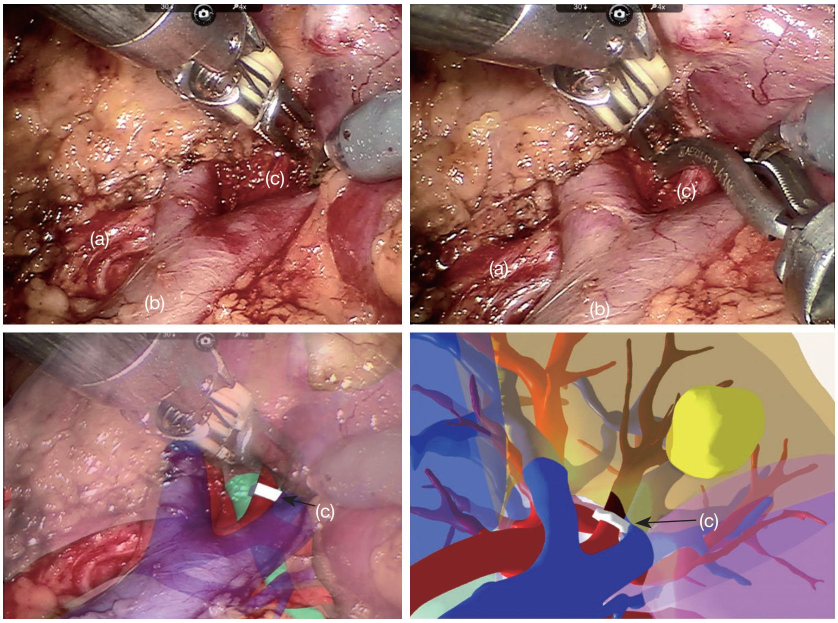

Figure 3 HR real-time navigation used to assist the location and isolation of vessels supplying the tumor. (a) Renal artery; (b) renal vein; (c) tumor supply artery. HR, holographic reconstruction.

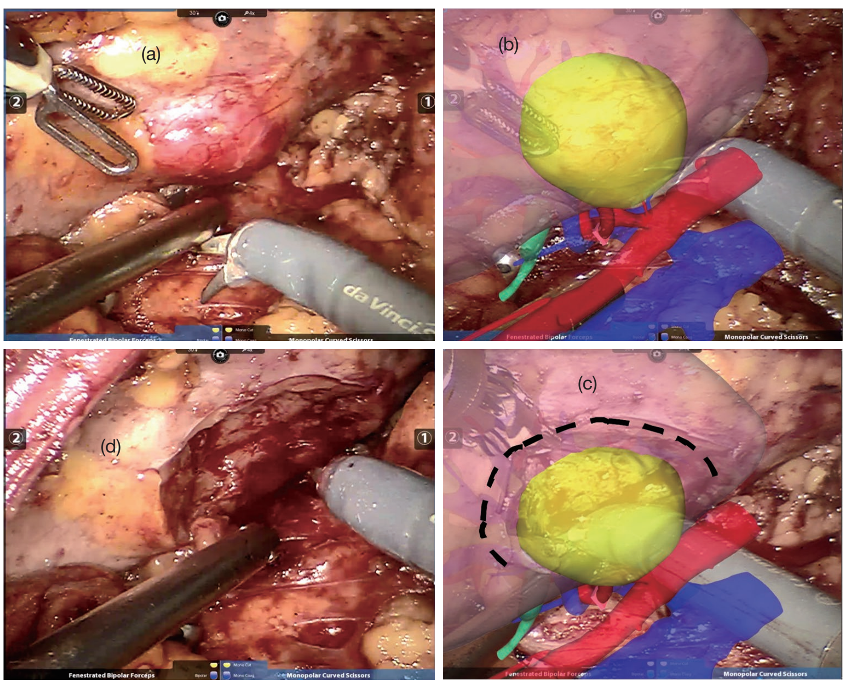

Figure 4 HR real-time navigation assisted to locate and resect endophytic tumor margin. (a) first step: isolate and confirm the tumor approximate location; (b) second step: real-time navigation to visualized the tumor precise margin and vessels by HR; (c) third step: resected the tumor according to the real-time navigation display; (d) fourth step: the complete resection endophytic tumor image. HR, holographic reconstruction.

Table 2 Pathology, surgical margin status, complications

Parameters	N (%)
Final pathology	
Clear cell	35 (85.4)
Chromophobe	5 (12.2)
Papillary	1 (2.4)
Perioperative complications	
Intraoperation	
Conversion to open	0 (0.0)
Adjacent organ injury	0 (0.0)
Blood transfusion	0 (0.0)
Postoperation	
Fever	7 (17.1)
Abdominal distention	14 (34.1)
Unhealing wound	3 (7.3)
Blood transfusion	0 (0.0)
Urine leak	0 (0.0)
Renal bleed	0 (0.0)
Positive surgical margin	0 (0.0)

Table 3 Operation time, WIT, EBL, perioperative GFR

Parameters	Mean ± standard deviation [range]
Operative time, min	115.3±20.3 [70–153]
WIT, min	18.7±3.9 [13–28]
EBL, mL	98.8±18.7 [60–141]
Perioperative eGFR, mL/min/1.73 m^2	
Diseased kidney preoperative operation	35.7±6.9 [27–45]
Diseased kidney postoperative 3-month	22.1±7.2 [19–38]

WIT, warm ischemia time; EBL, estimated blood loss; GFR, glomerular filtration rate; eGFR, estimated GFR.

NSS achieves similar oncological outcomes compared to radical nephrectomy for small renal tumors (20). NSS has been shown to significantly reduce the onset of chronic renal failure compared to radical nephrectomy. Indeed, the increased literature and American Urological Association guidelines advocate the implementation of PN in clinical stage T1a–T1b renal tumors where preservation of the renal parenchyma is recommended (21,22). For NSS, the advent of laparoscopic techniques, together with advancements in instrumentation and imaging, have led to improvements in precision renal tumor resections, which can maximally preserve the renal parenchyma and renal function (23). RA laparoscopic techniques have the following advantages: (I) 3D images of the operative field can be visualized with the naked eye; (II) the robotic arm does not fatigues, does not shake, and is equipped with 360 degrees of free rotation; and (III) the laparoscopic camera can be freely controlled by the surgeon. Thus, RA laparoscopic surgery is considered the second most important technical innovation after laparoscopic techniques (24).

Mixed reality technology, including augmented reality and virtual reality, is a new breakthrough in imaging technology. New visualization environments can be created by introducing virtual information into real-life scenarios, resulting in the coexistence of physical and digital objects and allowing for real-time interactions. Mixed reality technology enables precision surgical operations in all segments of surgical treatment (25). HR is a well-established and successful area of mixed reality technology (8,26). HR technology combined with RA laparoscopic systems can enhance surgical precision, resulting in less intraoperative bleeding, fewer postoperative complications, and faster rehabilitation for patients.

In our department, we found HR to be more exhaustive and precise compared to CTA when assessing the morphological location of the tumor. Visualizing the relationship between the blood vessels supplying the tumor and other renal arteries and vein was beneficial to developing the surgical plan and anatomical approach. The HR data also provided insights into possible difficulties of the surgery and possible intraoperative complications. In addition, the HR created 3D images of the tumor, blood vessel, kidneys, and other organs on the computer screen, and this was a useful tool during preoperative communications and discussions with the patients. Patients were able to gain a deeper understanding of the surgical modalities and content (*Figure 1B*), as well as the risks and possible postoperative complications. All this is important for improving doctor-patient relationships and patient compliance.

Real-time intraoperative navigation with HR is a revolutionary improvement and innovation in surgical operations. Previously, operations in traditional surgery procedure were performed on the basis of what could be

Table 4 Clinical data of patients treated with RAPN—a review of the published literature

Authors	Numbers	Time (min)	Size (mm)	PSM (%)	WIT (min)	EBL (mL)	eGFR DR (%)
Ilter Tufek	50	145	47.6	0	20.8	269	15
Michael W. Patton	90	196	NR	0	NR	150	11
Agnes J. Wang	40	140	25	1/40 (2.5)	20	136	NR
Brian M. Benway	129	189	28	5/128 (3.9)	19.7	155	NR
Monish Aron	12	242	24	1/12 (3.1)	23	329	7.4
Daisuke Motoyama	65	180	23 (median)	0	15 (median)	50 (median)	9.8
Jonathan S. Ellison	150	160	29	6/150 (4.0)	28.2	300 (median)	10
Matthew T. Gettman	13	215	35	0	22	170	NR
Sanjeev Kaul	10	155	23	0	21	92	NR
Courtney K. Phillips	12	265	14	0	26	240	NR
Craig G. Rogers	14	192	36	0	31	230	NR
Present study	41	115	35	0	18.7	99	16

Numbers: case numbers; time: total operation times; size: pathologic tumor size. RAPN, robot-assisted partial nephrectomy; PSM, positive surgical margin; WIT, warm ischemia time; EBL, estimated blood loss; eGFR DR, estimated glomerular filtration decrease rate (preop – postop diseased kidney); NR, no report.

seen in the operative field. However, the use of HR real-time navigation provided precise intraoperative guidelines, such as in cases where the vessels are hidden by other tissues or organs. HR can present a complete 3D image, allowing the surgeon to access the target directly and rapidly with minimal damage to surround vessels and tissues (*Figures 1C*,*3*,*4*). Without the support of HR, the surgeon can usually only seek out the renal artery and/or the secondary branches. However, with real-time navigation by HR, the surgeon can dissect and separate the renal vessels again, allowing for identification of the tertiary or even quaternary branch vessels. Clamping of the precise vessels supplying the tumor can effectively reduce intraoperative bleeding (*Figure 3*).

The aim of PN is the precise resection of tumors and the maximum preservation of healthy nephrons. This can be achieved by robotic surgery assisted by the HR navigation system. The robotic arm does not fatigue, does not shake, and has 360 degrees of free movement. Intraoperative real-time 3D imaging allows clear visualization of the tumor margins and the renal parenchyma. HR technology allows the user to rotate, magnify, and hyalinized the images surrounding the tumor margin. Even tumor margins on the opposite side or embedded deep inside tissues which cannot be visualized by the laparoscope camera, can be detected with HR (*Figure 4*). This allows the precise and complete removal of the tumor, enabling maximum preservation of nephrons with minimal damage.

There were several limitations to this study. First, this was a retrospective, single center study with a short follow-up period. Future multi-center studies with a longer follow-up period should be conducted to verify these results. Second, all the operations in our department were performed by a same surgeon and the influence of surgeons with different proficiency levels on the patient outcomes cannot be ignored.

Conclusions

The use of HR in RAPN resulted in shorter surgery time, shorter tumor resection time, and improved precision and rapid location of surgical targets. Therefore, real-time navigation with HR is a promising technology for RAPN.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All procedures performed in this study involving human participants were in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by ethics board of General Hospital of Central Theater Command of the People's Liberation Army (Number: [2018]012) and informed consent was taken from all the patients.

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