The Current Status and Challenges in Augmented-Reality Navigation System for Robot-Assisted Laparoscopic Partial Nephrectomy

Akihiro Hamada[1], Atsuro Sawada[1], Jin Kono[1], Masanao Koeda[2], Katsuhiko Onishi[2], Takashi Kobayashi[1], Toshinari Yamasaki[1], Takahiro Inoue[1], Hiroshi Noborio[2], and Osamu Ogawa[1](✉)

[1] Department of Urology, Graduate School of Medicine, Kyoto University, Kyoto, Japan
ogawao@kuhp.kyoto-u.ac.jp

[2] Department of Computer Science, Osaka Electro-Communication University, Osaka, Japan

Abstract. Robot-assisted surgeries have enabled surgeons to perform complex procedures more precisely and easily as compared with the conventional laparoscopic surgery. These new technologies have expanded the indications of the nephron-sparing surgery to cases that are anatomically more complicated. One of the challenging cases is that of the completely endophytic tumors because surgeons do not have any visual clues about tumor location on the kidney surface. In addition, these tumors pose technical challenges for their localization and resection, thereby likely increasing the possibility of perioperative complications. Since April 2014, we have been developing a visual support system for performing robot-assisted laparoscopic partial nephrectomy (RAPN) using the augmented-reality (AR) technology. The AR-based navigation system for RAPN can help identify the vasculature structure and tumor location easily and objectively. Moreover, image registration and organ tracking are critical to improving the accuracy of the system. Notably, tissue deformation, manual adjustment, and depth perception are the key elements for achieving precise image registration. Thus, console surgeons must effectively understand the properties and weak points of the AR navigation system and, accordingly, manipulate the laparoscopic camera and robot forceps to facilitate image registration and organ tracking. The cooperation of the console surgeon can result in a better collaboration between the real-time operation image and three-dimensional computer graphics models in the navigation system. We expect our system will offer significant benefits to both surgeons and patients.

Keywords: Robot-assisted laparoscopic partial nephrectomy (RAPN) · Augmented reality (AR) · Navigation system · Renal tumor

1 Introduction

The standard treatment for localized renal tumors is the nephron-sparing surgery [1]. The robot-assisted laparoscopic partial nephrectomy (RAPN) is an excellent and minimally

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invasive treatment that can achieve both cancer control and renal-function preservation. Robot-assisted surgeries have enabled surgeons to perform complex procedures more precisely and quickly compared with the conventional laparoscopic surgery because of both the clear visual field provided by three-dimensional cameras and precise motion by articulated arms. These new technologies have expanded the indications of the nephron-sparing surgery to cases that are anatomically more complicated.

One of the challenging cases is that of the completely endophytic tumors because surgeons do not have any visual clues regarding the tumor location on the kidney surface (see Fig. 1) [2, 3]. In addition, these tumors pose technical challenges for localization and resection, thereby increasing the distinct possibility of perioperative complications. Recently, some reports asserted the safety and feasibility of RAPN for treating endophytic tumors; however, the operations were performed only by experienced surgeons in these reports. Although the use of intraoperative ultrasound is recommended [4], it is not always adequate in assessing the precise border when the tumor is either completely endophytic or appears relatively isoechoic. The misidentification of the tumor location may result in longer operative time, positive surgical margin, and unnecessary loss of normal kidney tissue. Therefore, to avoid predictable perioperative complications, surgeons, especially novice ones, must support the visualization of the tumor location.

Since April 2014, we have been developing a visual support system for RAPN using the augmented-reality (AR) technology. Appropriate image guidance using the AR navigation system can offer a potential clinical advantage for performing accurate anatomical identification and precise resection of tumors, reducing the possibility of perioperative complications.

In this report, we describe the current status of our navigation system and the underlying problems thereof via our in-vivo human experiences.

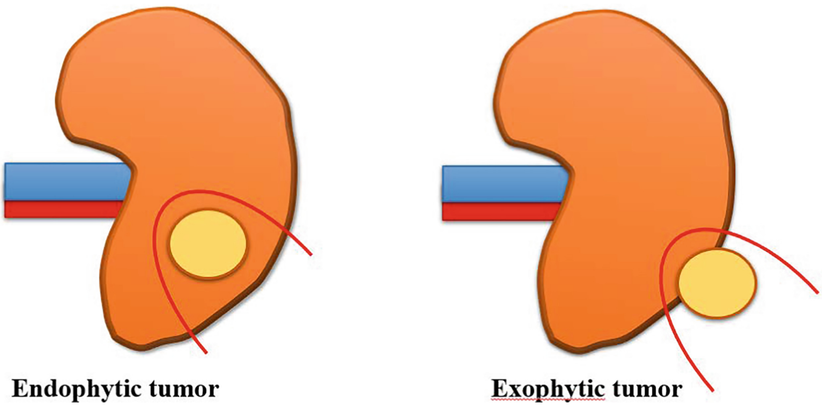

Fig. 1. Difference between an endophytic and exophytic tumor.

2 Surgical Technique of RAPN

We used either the transperitoneal or retroperitoneal approach depending on the tumor location. Patients were placed in the lateral position. After placing the robotic ports, the da Vinci Xi Surgical system (Intuitive Surgical, Inc., Sunnyvale, CA) was docked. The surgical procedures included the following: mobilization of the bowel, exposure of the kidney, identification of the hilum, and dissection of the renal artery and vein. Subsequently, the kidney was defatted, and the console surgeon identified the tumor depth and margin via robotic ultrasound. After identifying the tumor location and adequate margin of normal parenchyma, the hilum was clamped, following which the tumor was resected, and the defect was reconstructed by suturing the renal capsule (see Fig. 2).

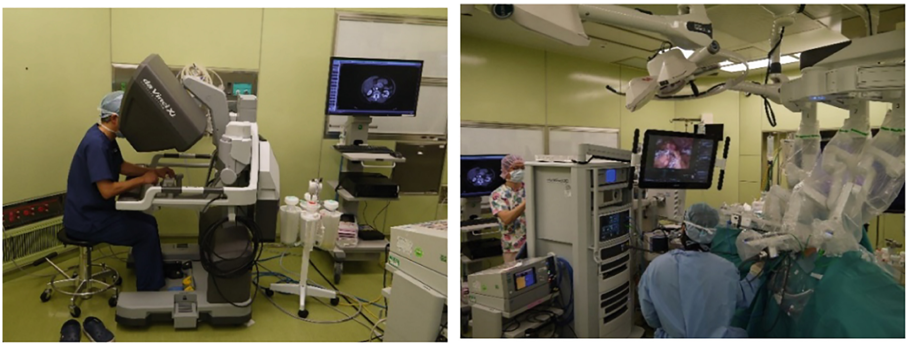

Fig. 2. Overview of the RAPN. (Left: console surgeon, Right: assistant surgeon)

3 Current Status of the Navigation System

We previously reported about our AR navigation system for RAPN [5]. Before surgery, we prepared three-dimensional computer graphics (3DCG) models that included the graphics of kidneys, arteries, veins, tumors, and urinary tracts, all of which were obtained from the DICOM images of computed tomography (CT) scans with SYNAPSE VINCENT (FUJIFILM Holdings Corporation, Tokyo, Japan) (see Fig. 3). The 3DCG models were projected on the console of the operator by using the Tilepro function and on the operating room monitor. An assistant doctor manually controlled the projected 3DCG model of the visceral structures during the surgery. The position and orientation of the 3DCG model were calculated using the optical flow of the endoscopic camera images, thereby enabling the 3DCG model to track the laparoscopic images semi-automatically.

We have applied this surgical navigation system for a total of 38 RAPN cases from November 2014 to June 2019. The main purpose of this system is to show the hilum structure and identify the tumor location, especially for endophytic tumors. However, some barriers exist toward achieving a practically useful navigation system for console surgeons.

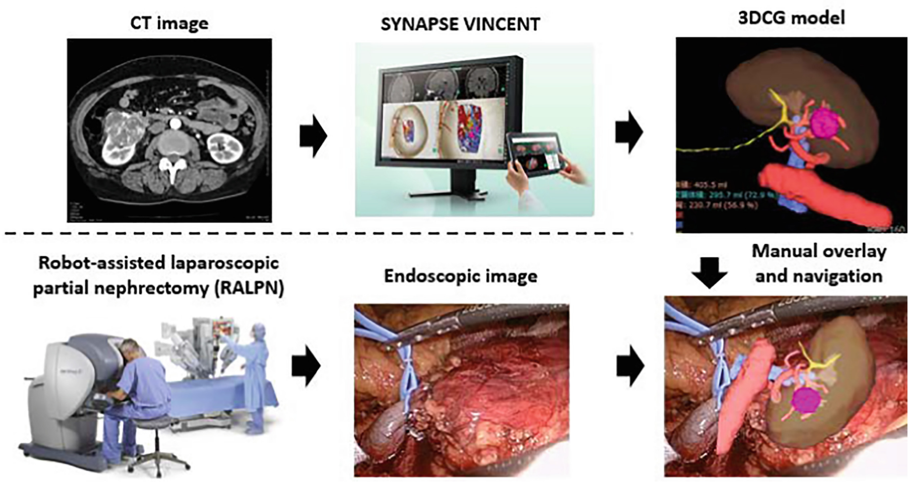

Fig. 3. Overview of our current AR navigation system.

4 Challenges to Overcome

Applying the 3DCG image onto intra-abdominal kidneys poses many challenges. The kidneys do not stay at the same position during the surgery relative to the surrounding organs. Moreover, the size and shape of the kidney during operation also varies both because of clamping the hilum and manipulation of the organ and dissection [6]. We describe the current problems by focusing on two steps, namely, image registration and organ tracking.

4.1 Image Registration

The registration of the 3DCG image to intraoperative organs is the first step to overlay. We intend to align the preoperative 3D image with laparoscopic image by matching corresponding locations such as hilar vasculature, kidney shape, kidney-surface characteristics, and surrounding anatomic structures. The registration must be highly accurate to indicate adequate margin from the tumor when determining the resection line.

We consider the following three reasons that decrease the accuracy of image registration: tissue deformation, manual adjustment, and depth perception.

Tissue Deformation. Tissue deformation is one of the major challenges during operation. The 3DCG model comprises preoperative CT images, which reflect the kidney shape for the prone position of the patient. However, during the actual operation, the kidney is deformed via several factors such as lateral position of the patient, pneumoperitoneum, surgical dissection, physiological cardiorespiratory pattern, and clamping renal vessels [6]. Therefore, to achieve precise image registration, the preoperative 3DCG models must reflect the real-time laparoscopic image that changes at every step of the surgery.

Manual Adjusting. In our navigation system, assistant surgeons operate the models to manually superimpose the image onto the laparoscopic image. Therefore, the image-matching quality depends on the experience and knowledge of the assistant surgeons. However, it is sometimes challenging to overlay the images because there are only a few landmarks on the kidney surface. Therefore, the kidney surface must be exposed to some extent for performing accurate surface-based registration (see Fig. 4).

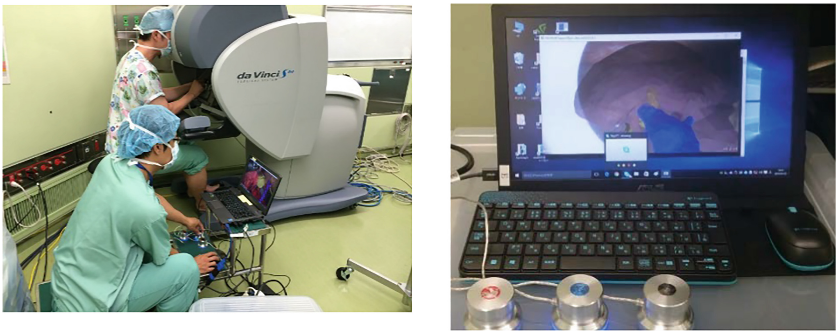

Fig. 4. Assistant surgeon manually operating the 3DCG models. (Left: The console surgeon and assistant surgeon, Right: Controller of the 3D models)

Depth Perspective. The da Vinci surgical system is equipped with stereo cameras, which provide excellent 3D images. During the operation, we can feel depth perspective that is very useful for precise operation. However, overlay 3DCG models do not exactly reflect the same depth perspective as that reflected by the real operation image. Therefore, a depth perspective gap is formed depending on the distance from the laparoscopic camera to organs, for example, between the upper and lower poles of the kidney. To achieve complete image registration, the 3DCG models must reflect the same depth perspective in the real-time images. Therefore, the tumors in the lower pole are less effected by the depth-perspective gap (see Fig. 5).

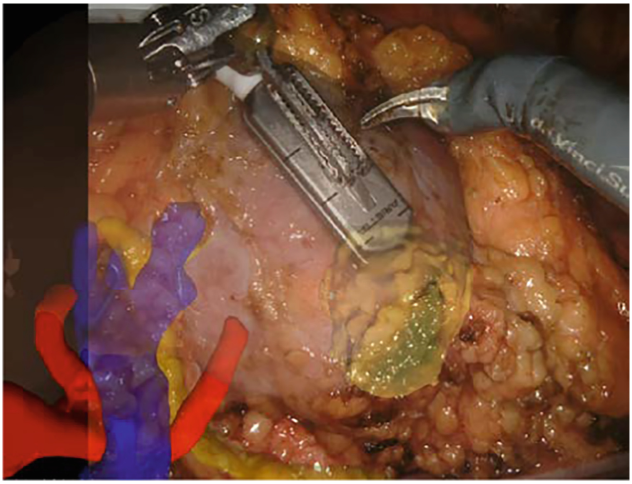

Fig. 5. The tumor in lower pole is easier to overlay.

4.2 Organ Tracking

Another issue that affects the accuracy of image registration is the insufficiency of the tracking performance. The overlaid registered image will be expected to lock to the operative view and synchronously move with the organ. We use the optical flow system of the endoscopic camera images; the system calculates the position and orientation of the 3DCG model and enables the 3DCG model to semi-automatically track the laparoscopic images. During the operation, the characteristic landmarks of the kidney change continuously as surgeons mobilize the neighboring organs and raise the kidney to dissect the vasculature. The surrounding fat and bleeding can also decrease the accuracy of organ tracking.

In robot-assisted surgeries, surgeons rely only on visual information because of the lack of haptic feedback. Therefore, the laparoscopic camera repeatedly moves back and forth to confirm the overview of the operation field and detailed structures such as small vasculatures. However, our tracking system cannot follow the quick motion of the camera, resulting in the failure of image registration.

5 Future Plans

5.1 Development of New Technology

Surface-Matching System. To overcome the challenges during image registration, we are developing a new registration method equipped with a surface-matching technique [7]. In this system, an object can be detected and localized by combining both intensity and depth data. This technique can assess the position and posture of the kidney by identifying the common features between 3D models obtained using real-time surgical images and 3DCG models obtained using preoperative CT images. The validation of the technique is presently in progress (see Fig. 6).

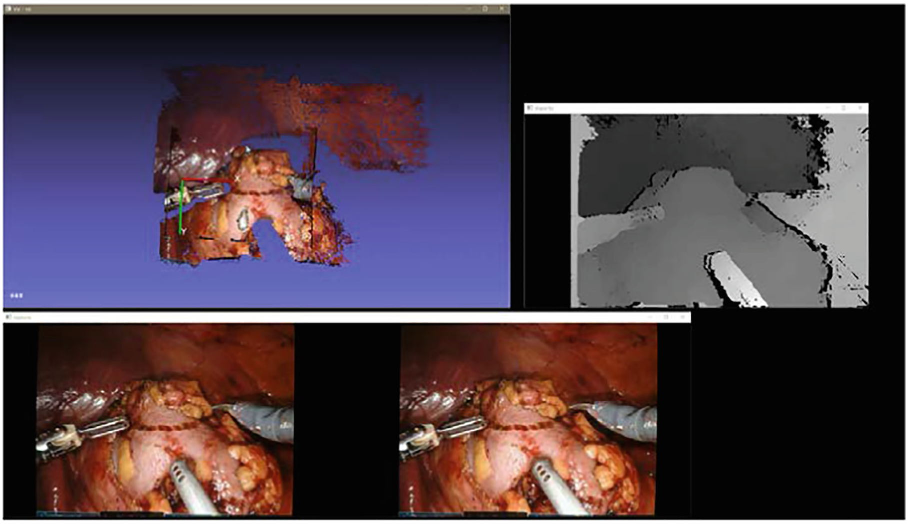

Fig. 6. Disparity map (upper right) and point cloud (upper left) generated from the stereo images simultaneously captured during surgery for the surface matching.

Simultaneous Localization and Mapping. Since April 2018, we have been testing the simultaneous localization and mapping (SLAM) technique to achieve a totally automatic tracking system [8]. The SLAM system imports the information of the characteristic features from the operation images, estimates its own location, and creates a map of its surrounding environment. The SLAM technique might improve the tracking ability of our navigation system. Thus far, models cannot follow the quick motion of the endoscopic camera even when the SLAM system is working, and when the camera returns to the endoscopic port, it resets the SLAM system. To overcome these problems, we are trying to install Stereo SLAM system. To utilize Stereo SLAM, we first conducted stereo endoscopic camera calibration and acquired the camera parameters (see Fig. 7a). Using this parameter, Stereo SLAM during surgery was tested in July 2019 and we confirmed that the tracking robustness was improved than the conventional SLAM (see Fig. 7b).

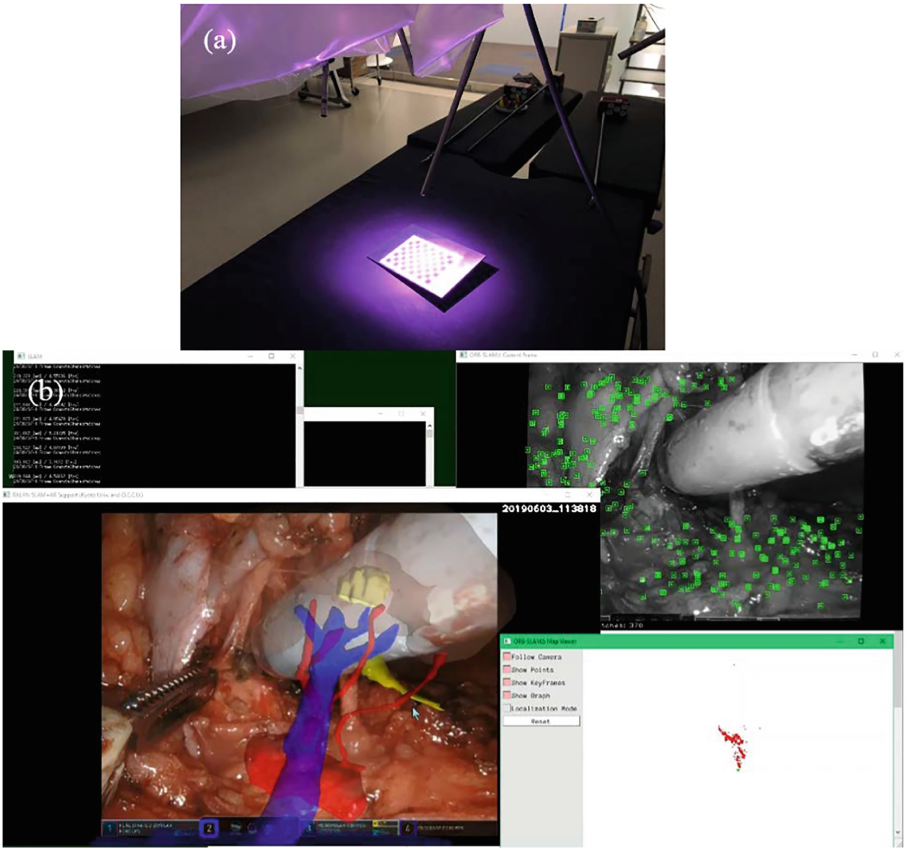

Fig. 7. (a) Stereo camera calibration in vitro setting. (b) Stereo SLAM during surgery.

5.2 Cooperation of the Surgeons

As describe previously, many challenges still exist to achieve a practical system. Thus far, the understanding of this system and corporation of the console surgeons is critical to achieving better collaboration.

The important points for achieving accurate image registration are as follows:

- remove the fat tissue surrounding the kidney as widely as possible;
- put the kidney on a flat position;
- see the kidney from the side view (not from the tangential direction) to reduce the depth-perspective gap when overlaying the 3DCG model on the real operative image (see Fig. 8).

The important points for achieving accurate organ tracking are as follows:

- move the camera slowly;
- do not pull the camera into the camera port.

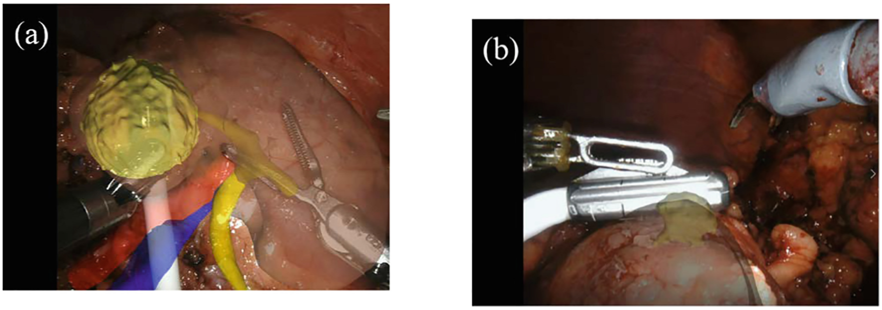

Fig. 8. 3DCG model on a real operative image. (a) Side view. (b) Tangential view.

6 Discussion

The AR navigation system for RAPN can help identify the vasculature structure and tumor location easily and objectively. Consequently, we can expect better surgical outcomes such as short operative time, less blood loss, and reduced complications. The visually supporting system can compensate for less surgical experience and help improve the learning curve of novice surgeons. In addition, less invasiveness of the surgery may reduce the perioperative cost. Furthermore, as all the staffs in the operation room, such as assistant doctors, nurses, and other medical staffs, can see the projected 3D images, sharing information about the proceeding of the surgery.

However, our current navigation system still has some defects associated with tumor localization. The ideal AR navigation system would have the ability of flexible tissue deformation, fully automatic image registration, and organ tracking. Image registration is the first step that must be improved to achieve the accurate system. In addition, tissue deformation, manual adjustment, and depth perspective are the key elements to achieving precise image registration. Surface-matching system might adjust the image automatically. Accordingly, SLAM is a new technology for the intraoperative tracking of an image. However, even these new technologies cannot work smoothly when the operation view is changing significantly. Although there have been several reports that examined the AR system for RAPN, much work need be done before AR surgical systems can be used for performing accurate image-guided tumor resection [6]. Thus far, console surgeons must understand the properties and weak points of the AR navigation system and, accordingly, manipulate the laparoscopic camera and robot forceps to facilitate both image registration and organ tracking. In addition, the cooperation of the console surgeon can help achieve a better collaboration between the real-time operation image and 3DCG models in the navigation system.

Patients merit the utmost priority in any surgery; therefore, a time-consuming, inaccurate system is not practical. The "Trifecta" outcome is a concept that comprises the following three criteria: warm ischemia time $<$ 25 min, negative surgical margin, and no perioperative complications [9]. To increase the Trifecta achievement rate is one of the goals for achieving better surgical results [10]. Although our current navigation system partially supports the identification of the tumor location, it must be improved to achieve higher accuracy and clinically validate the improvement of perioperative outcomes.

7 Conclusion

We developed a novel AR navigation system for RAPN. Our navigation system performed appropriately and partially helped to localize the tumor and determine the resection lines. However, the current challenge lies in improving both image-registration and organ-tracking performances. We expect our system will offer significant benefits to both surgeons and patients.

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