Chapter

The Three-Dimensional Virtual Surgical Simulation and Surgical Assistance for Optimizing Robotic Partial Nephrectomy

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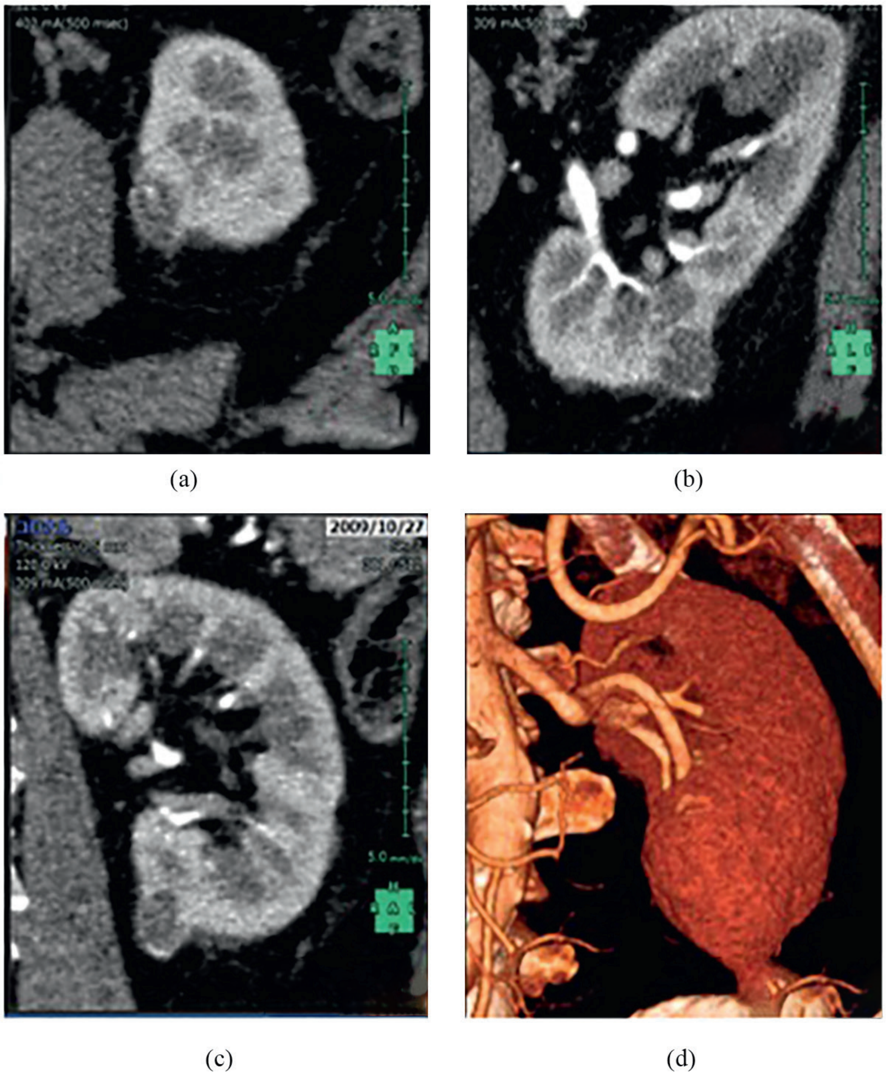
Abstract

Robot-assisted partial nephrectomy (RAPN) has been accepted as the standard treatment recommended for relatively small renal mass or even the T2 renal carcinoma in experienced hospitals as Nephron Sparing Surgery. To obtain better RAPN surgical outcomes, the understanding of surgical anatomies such as the position of intrarenal structure and the positional relationship of each structure should be detailed in a three-dimensional (3D) manner. The 3D virtual surgical simulation for partial nephrectomy based on the image segmentation method with high-resolution CT can provide the 3D anatomical details of the renal tumor focusing on their relationships with the arterial and venous branches as well as with the intrarenal portion of the urinary collecting system. This imaging application is also used as image guidance during the surgery, and it indicated that it provides the improvement of clinical outcomes such as the duration of hospitalization, transfusion, and major postoperative complications as well as conversion to radical nephrectomy or open partial nephrectomy. In this chapter, we describe the basics of the 3D imaging assistance methods for partial nephrectomy and the benefit of 3D virtual surgical simulation in optimizing the outcome of the RAPN.

Keywords: partial nephrectomy, robot-assisted partial nephrectomy, segmentation, 3D surgical simulation, image-guided surgery

1. Introduction

The number of stage 1 renal cell carcinoma has shown a significant increase in this decade. This trend was been brought by the improved modality of the screening imaging technology, such as ultrasound or CT imaging. The surgical treatment has been recognized as the standard surgical procedure for the treatment of early-stage renal cancer. Nephron sparing surgery (renal function-preserving surgery) has become the recommended treatment option for small-diameter renal tumors (small-diameter renal cancer) [1]. Comparing the oncological results after radical nephrectomy and partial nephrectomy, the outcomes of both surgical methods are equivalent; in addition, partial nephrectomy provides better preservation of renal function [2]. With partial nephrectomy, it may be considered lower the risk of cardiovascular and metabolic sequelae that would eventually turn into better overall survival for the patient comparing radical nephrectomy [3–5]. Therefore, at present, Nephron sparing surgery is positioned as the standard treatment for T1 small-diameter renal cancer. Partial nephrectomy is preferred for the following T1a tumors, and partial nephrectomy is recommended for T1b tumors between 4 and 7 cm, if possible [1, 6, 7]. Robot-assisted partial nephrectomy (RAPN), in particular, with the high-resolution 3D stereoscopic view and with multiple joints in robotic arms has been reported to have better treatment results than open surgery and laparoscopic surgery, such as preservation of function and reduction of perioperative complications [8, 9]. Today, at high-volume centers, the indication for partial nephrectomy has been gradually expanding with the robot-assisted procedure for selectedT2 cases. With increased tumor size and stage, PN becomes more challenging surgery, it may result in a higher risk of perioperative complications such as severe blood loss, urinomas, and arteriovenous fistulas. These are known as "Risk benefit trade-offs between partial and radical nephrectomy", so it was recommended that PN indication for large tumor should be considered more selective, and specific for patient and tumor factors [7, 10].



(a) (b)

(c) (d)

Figure 1.
The comparison of two-dimensional (2D) images of CT with axial (a), coronal (b), and sagittal (c) images and 3D CT volume rendering image (d).

Partial nephrectomy is a procedure that cuts into the blood-rich renal parenchyma, requiring complete excision of the tumor and precise repair of damaged renal structures. It was demonstrated that the degree of difficulty varies depending on the patient factors such as comorbidities or anatomical factors, and operators skillset and the learning curve is relatively long comparing other urological operations [9–12]. Due to the complexity of surgical procedure, it is considered that presurgical evaluation and surgical planning are quite important for each case. Surgeons should understand the surgical anatomy of the target kidney and tumor, especially, the position of renal structure, and the positional relationship of each structure should be known in order to optimize the surgical technique and achieve better surgical outcomes [10]. For a detailed understanding of the relationship of the hilum to the anatomy, it has previously been performed using two-dimensional (2D) image data (coronal, sagittal, and axial images) of computed tomography (CT) volume rendering for evaluation of these anatomical factors (**Figure 1a**–**c**) [13, 14]. Surgeons had to use their cognitive abilities to simulate the anatomy of the kidney and tumor as three-dimensional information while referring to those 2D images. For experienced urologists, it was probably easy to recall 3D information from 2D images; however, it is unclear whether all urologists can accurately reproduce the detailed anatomy and its complexity. Since 2012, there have been many reports to describe the befit of 3D CT volume rendering images for partial nephrectomy as the surgical support (**Figures 1d** and **2a**) [13].

However, only by the 3D-CT volume rendering, it was difficult to extract the urinary system or renal vein ant tumor at the same time, and it also enables to perform the volumetric analysis. To overcome the difficulties of 3D-CT volume rendering, one imaging technique called “segmentation” was developed as the image processing method (**Figure 2b**).

The segmentation process identifies the position information of each part of the organ and extracts one organ as a segment. Because the intrarenal anatomical structures of the kidney can be opaqued or removed as 3D models, interactive anatomical evaluation can be performed. It becomes possible to visualize the physical structure [15]. Since 2015, the Department of Urology, Juntendo University, has been using segmented

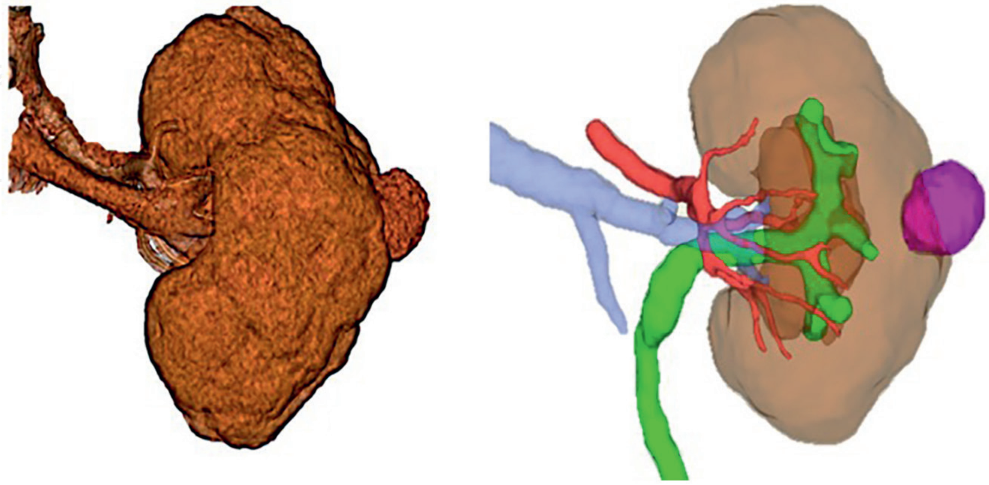

(a) (b)

Figure 2.
The comparison of 3D CT volume rendering image (a) and 3D segmented image (b). With 3D CT volume rendering image, it is difficult to distinguish renal organs at one glance. The 3D segmentation makes it easy to recognize the renal organs. This imaging process developed one step further to “image understanding” by recognizing organs as 3D images volume matrix.

3D images based on preoperative CT images to understand the anatomical complexity of renal tumors in RAPN and has been useful in preoperative planning [15, 16]. Furthermore, this imaging technology can also be used for surgical navigation during surgery and is extremely useful as an image reference during the actual surgery.

In this chapter, I will discuss the imaging technique for optimizing Robotic Partial Nephrectomy in surgical simulation and surgical assistance using 3D virtual surgical simulation.

2. Renal anatomical structures and 3D Segmentation

As mentioned earlier, at the partial nephrectomy, the surgeon cuts into the blood-rich renal parenchyma and removes the tumor and repairs damaged renal structures without hemorrhage and urine leakage. During all these processes, the surgeon needs to understand the detailed anatomy of the vasculature (renal artery and renal vein), urinary system, renal cyst, tumor(s), and other structures within or surrounding the kidney (**Figures 2b**, **3** and **4**).

In general, the renal artery is reaching from the main renal artery to the segmental artery, the interlobar artery, the arcuate artery, and the interlobular artery branch to the glomerulus. The anatomical distribution of renal arteries is divided into five segments including an apical, upper, middle, lower, and posterior segmental artery. Because each artery does not have adequate collateral circulation, the ligation of the segmental artery causes irreversible ischemia in that area of blood supplied by teach segmental filed [10, 13, 17].

This anatomical feature allows the surgeons to segmental resection only by segmental ischemia at the partial nephrectomy. All segmental branches arise from the anterior segmental artery, except for the posterior segmental branch, which arises from the posterior segmental artery. However, there are some anatomical variations are known in the distribution of the renal arteries. In the variation, the lower renal segmental artery may arise from the main renal artery. Also, there may an accessory artery also known as multiple renal artery or duplicate renal artery that arises from the

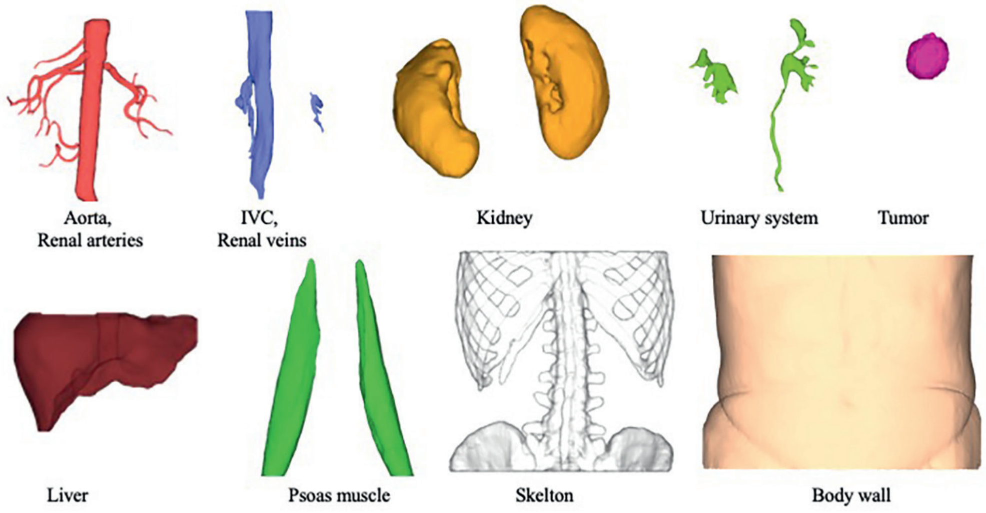


Figure 3.
At the segmentation process, renal anatomical structures the anatomical structures (aorta, renal artery, IVC, renal vein, kidney, urinary system, tumor, and other structures within or surrounding the kidney) are extracted from a different phase CT data using image recognition algorithm.

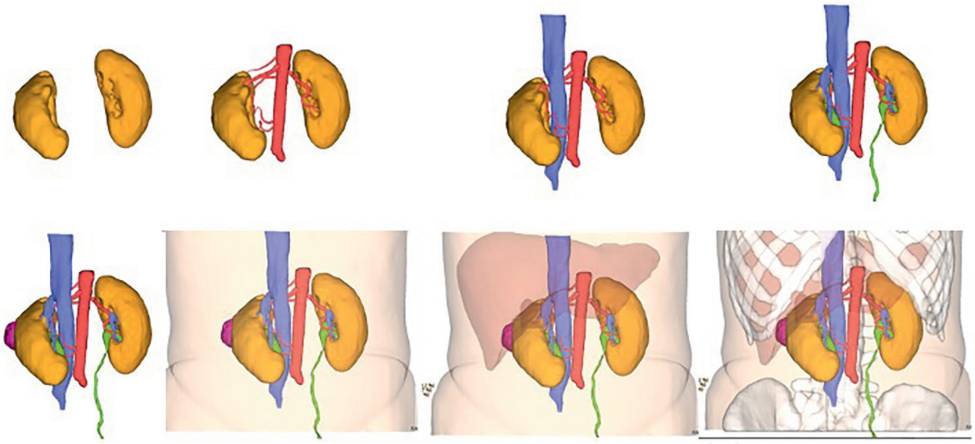


Figure 4.
3D structural images are combined together into one 3D image with registration technology. The extracted anatomical structures can change their transparency of the structural image for the easiest understanding, also organ volume such as tumor volume or renal volume can be calculated.

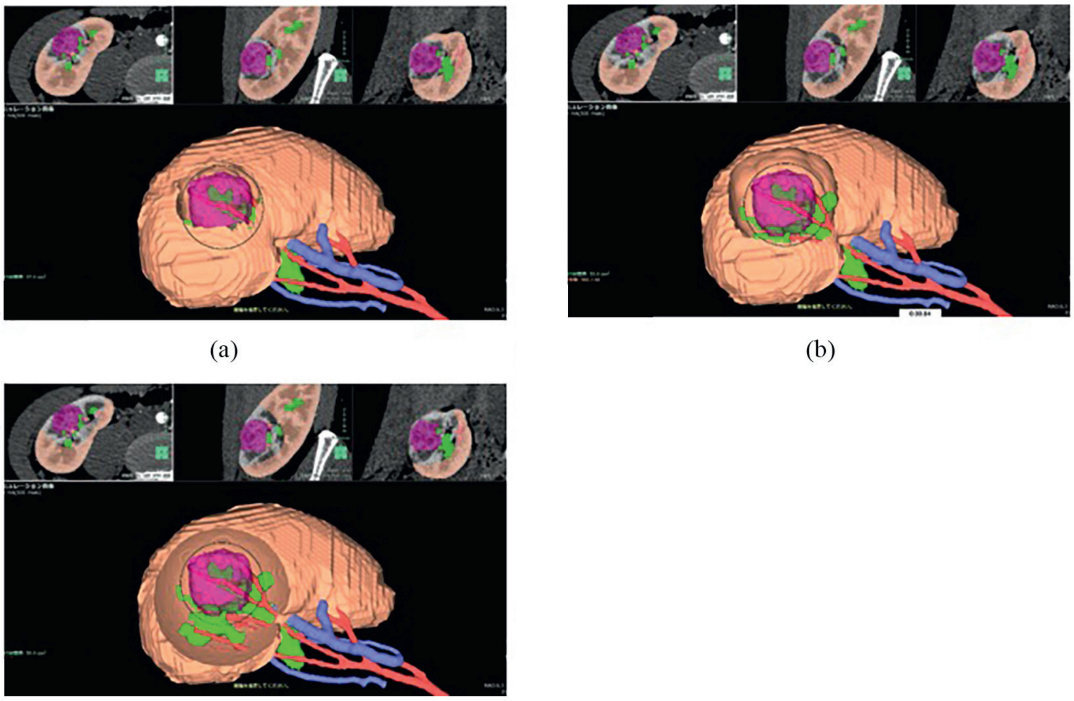
abdominal aorta directly and does not pass through the renal hilum [10]. The multiple renal arteries are regarded as the persistent embryonic lateral splanchnic arteries. The renal artery originally had multiple supply vessels from the aorta to the mesonephros during embryogenesis, but during the development process, two or more supply vessels remained on one side. The frequency of these duplicated renal arteries is estimated at 15% [10]. These anatomical variations of renal arteries have a great impact on actual partial nephrectomy surgery. If the surgeons know the detailed information about the anatomical distribution of the renal artery and operation time can be shortened and become safer and more reliable. The segmental clamping technique is one of the promising procedures to reduce the renal ischemic damaged area to preserve renal function. For effective segmental arterial clamping, the surgeon needs to identify the renal target artery in a 3D manner to get the essential ischemia damage for the resection of the tumor. Gill et al. reported super-selective arterial clamping in 2012 as the anatomical partial nephrectomy [18]. They used 3D segmentation to get the semitransparent tumor and renal arterial branches remain opaque. The 3D segmentation made it possible to see interrelationships of tumor vis-à-vis intrarenal segmental arterial branches, and such anatomical detail was necessary to operate on challenging tumors. The 3D segmentation is a medical image-aided tool that provides localization and assessment of organ size and shape. Kidney segmentation involves identifying the location information of each part of the kidney from high-definition CT, etc., and extracting one organ as a segment (**Figure 3**). The original computational 3D segmentation tool in developed in Japan in 2012 for the liver extraction tool and has been applied to the kidney in 2014 by Komai et al. [19]. In the past few years, 3D segmentation analysis for renal surgery has been applied in many countries, and it has been reported in some literature [19–24]. Today, with the computational algorithm, it is relatively easy to extract blood vessels from arterial phase CT imaging data. The renal arteries below 2 mm diameter and renal vessels are able to 3D segmentation by image recognition algorithm using the computer automatically. Also, the renal parenchymal and cortical regions can be extracted by the computational calculation with imaging software automatic tracing the edge of each kidney from CT images. The various image recognition algorithms were reported by researchers [19–24]. In addition, not only the blood vessels but also the renal tumor, the ureter, or the renal pelvis can be extracted automatically by using image recognition algorithms from the urography phase.

By combining extraction of the liver, bone, and body wall, now the surgeon can virtually reproduce all organ imaging required for performing the renal surgery by himself (**Figure 4**). The 3D segmentation processing improved medical imaging one step further to “image understanding,” in other words “imaging diagnosis” by recognizing organs as 3D images volume matrix. By performing 3D segmentation processing, the 3D map of the kidney organs can be produced as the computational volume data. Since it is the computational volume data, it is possible to modify the visualization interactively and calculate the image volume easily. The anatomical structures can be seen by changing the transparency of the structural image, and each organ volume such as tumor volume or renal volume is calculated. In addition, image processing such as measuring and comparing the volume and cutting out the surroundings at a certain distance is possible.

3. 3D-virtual surgical simulation and 3D-image guided surgery

The idea of simulating surgery using medical images has been examined for a long time; however, it has rapidly progressed and spread in this decade.

The reason for this progress is the improvement in computational power used for image processing and the development of 3D image-processing software. They have become more powerful and cheaper than before, and they have come to be offered as affordable medical equipment. The 3D-virtual surgical simulation consists of the following four steps [1]. The first step is acquiring CT DICOM data and importing the imaging data to the image-processing software [2]. The second step is the


(a)

(b)

(c)

Figure 5.
In the surgical simulation, the surgeon can simulate the width of the resection margin size and resection method. Setting the cut surface with an optimal tumor margin with (a) resection margin; 1 mm, (b) resection margin; 5 mm, (c) resection margin; 10 mm. The surgeon can predict the involvement of the urinary collecting system or vascular system on the cutting surface by surgical simulation. The simulated resection volume and residual parenchymal volume can be calculated by CT volumetry.

segmentation of the renal structures (renal artery and renal vein, urinary system, renal cyst, tumor, and other structures within or surrounding the kidney) from a different phase of CT data, by imaging software (**Figures 3** and **4**) [3]. Then we perform 3D-virtual surgical simulation using the imaging software. With the software, we can simulate the two different resection methods, the enucleation technique and wedge resection technique, with any surgical margin size setting (**Figure 5**, Video 1). In the enucleation setting, the surgeon can simulate the width of the resection margin size for virtual enucleation. At the wedge resection setting, the surgeon can perform the simulation with setting by both the cut angle and resection margin for virtual resection. We can predict the involvement of the urinary collecting system with surgical simulation. If the urinary collecting system appeared on the planned cut surface, it means that the urinary collecting system was involved in the resection field, and the surgeon needs to decide to cut the collecting system or gently peel away it from the tumor. The imaging software also can calculate each resection volume based on CT volumetry and residual parenchymal volume of the healthy kidney [4].

The final step is the assessment of the arterial supply area for selective clamping. It is the computational approximation of vascular territories based on Voronoi decomposition. With this computational 3D Voronoi decomposition, renal arterial territories were calculated according to each arterial branch as the central point of the blood-supplied segment (**Figure 6**, Video 2).

For the 3D-image guided surgery, we connect the imaging software to the da Vinci system through digital video interface (DVI) input ports (**Figures 5** and **6**). We can see the real-time 3D-image surgical simulation on the surgeon's console of the da Vinci surgical system as the reference, using TilePro multi-input display. Initially, the surgeon's console display of the da Vinci shows the endoscopic view. In the use of TilePro, the images of 3D-image surgical simulation simultaneously appeared just

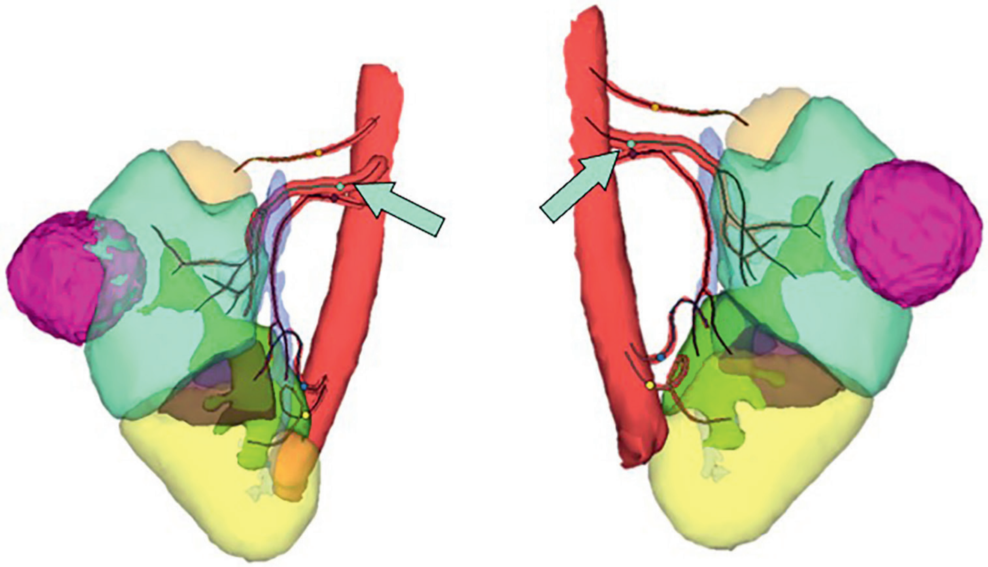


Figure 6.
The vascular territory (light green area) belonging to the selected targeted artery (light green arrow) branch is shown in a color-coded 3D model. The patient had five right renal arteries and a 2.5 cm tumor on the lateral side of the mid-renal pole. Vascular image analysis was performed to identify to know which artery supplied the tumor. Vascular analysis revealed that the second renal artery (light green arrow) is the only target artery to supply the tumor and 3 mm resection margin, so in this case, surgery was performed with a selective clamping technique on the targeted second artery only (the light green point was target point). The operation was safely completed without the need for an additional vascular clamp or blood loss.

below the standard endoscopic view (**Figures 7–9**), and the surgeon refers to their surgical plan to execute the same operation as they planned. The surgeon can identify the renal structures by manipulating the image in real-time 3D imaging; it allows the

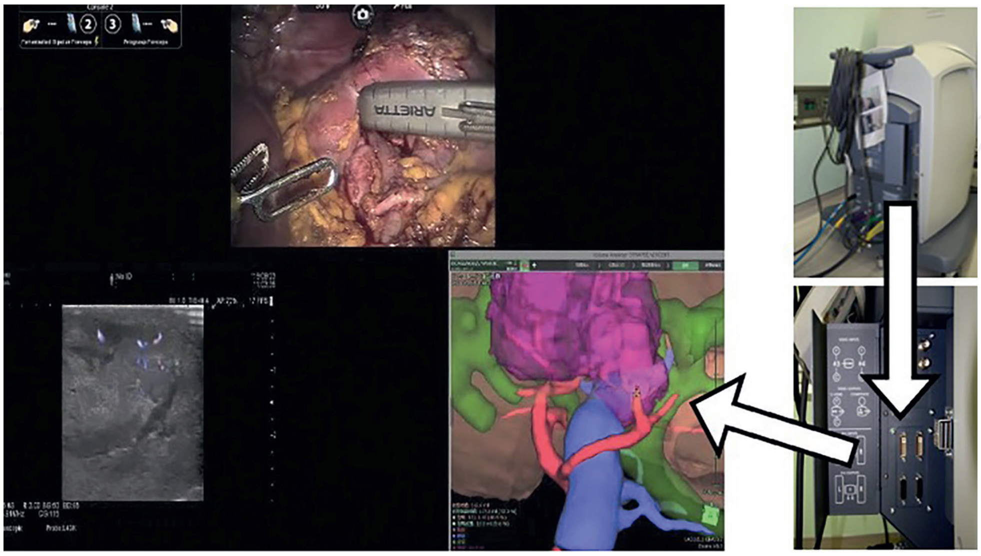


Figure 7.
The real-time 3D-virtual surgical simulation can be seen in the TilePro multi-input display on the surgeon's console of daVinci surgical system through digital video interface (DVI) ports on the backside. The simulated surgical plan in 3D volume-reconstructed images with key anatomical structures became available. The surgeon can identify the anatomical structure with ultrasound to complete the planned surgery correctly.

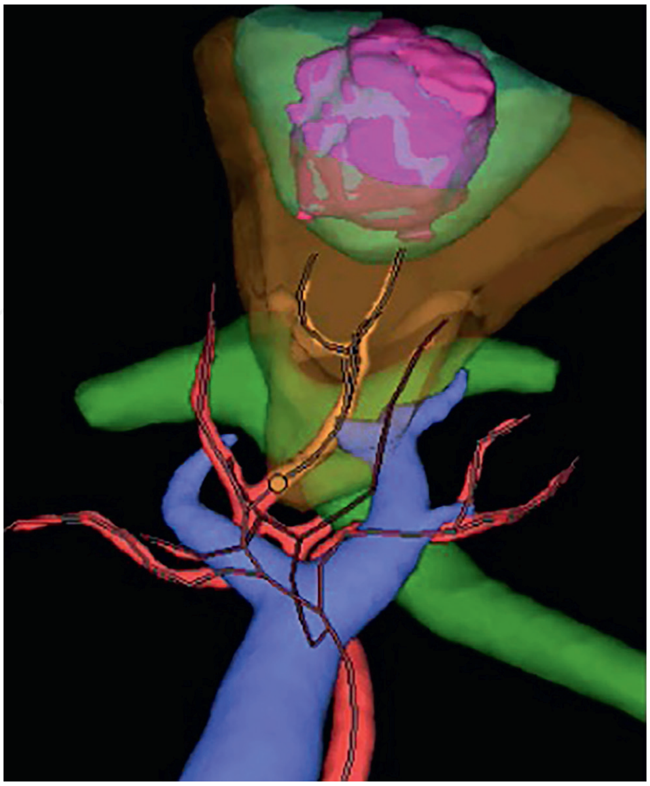


Figure 8.
The 3D-virtual surgical simulation determined that the resection area of the tumor (blue area), tumor (pink area), and regional ischemic area (brown area) by the selective arterial clamping at the third branch of the left renal artery (yellow dot), which was located below the left renal vein.

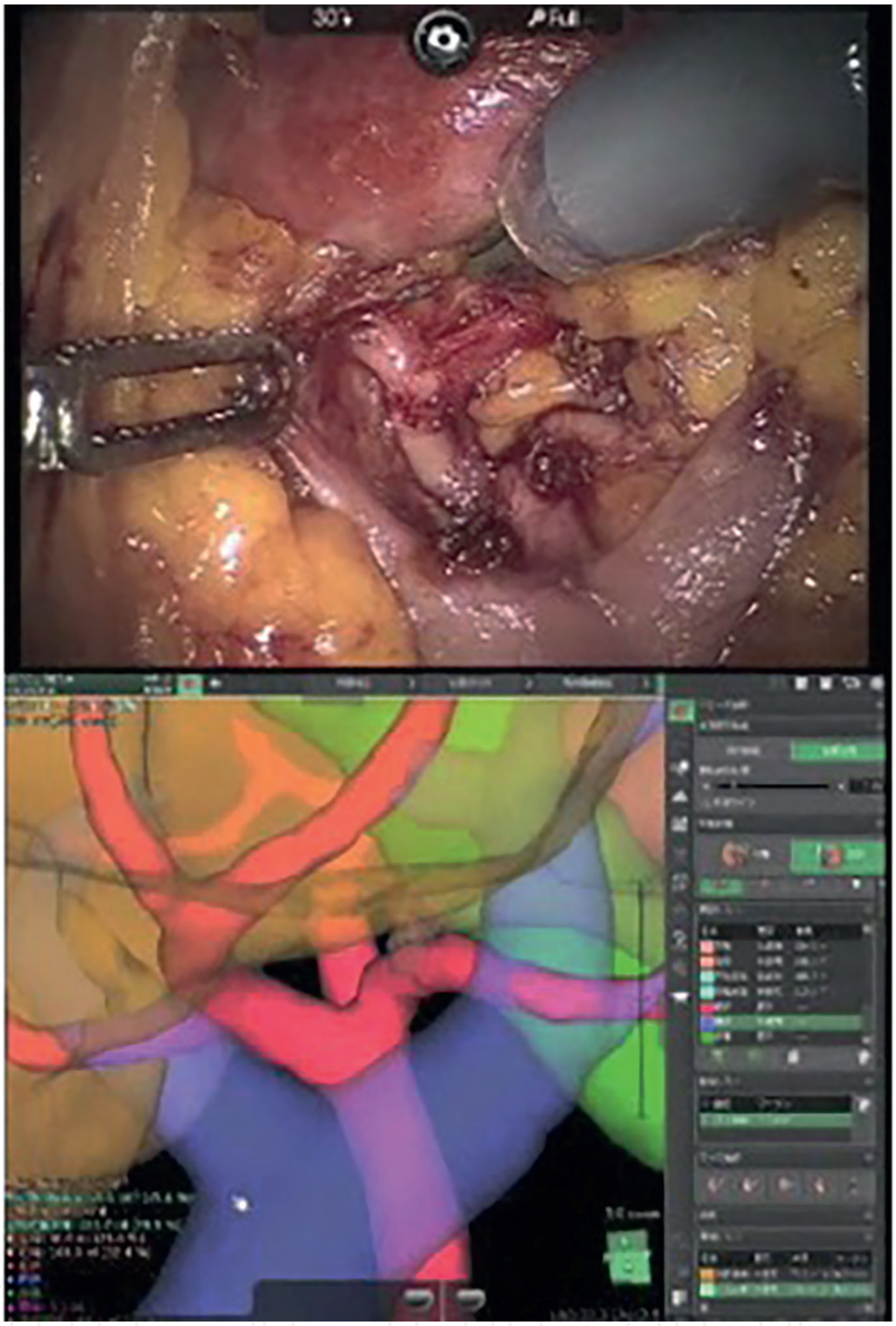


Figure 9.
A surgeon's console display with an endoscopic surgical view (top) and 3D-virtual surgical simulation (bottom) to identify the targeted vasculature after a renal hilum dissection. The top shows the actual surgical field, the renal arterial branches were already exposed at the second to third branch beyond the left renal vein. The bottom shows a real-time 3D-virtual surgical simulation image adjusted to the surgical field.

surgeon to find the key anatomical structures and cutting angle to adjust in the real operation field.

The Clinical benefit of the 3D-virtual surgical simulation and surgical assistance. Since 2014, there are some supportive publications reported about the 3D-virtual surgical simulation using this segmentation technology for RAPN from Japan. In 2014, Komai et al. demonstrated the surgical planning and surgical simulation by 3D segmented images for open partial nephrectomy [19]. In addition, in 2015, Isotani et al. reported that the 3D-virtual surgical simulation was able to provide the identification of tumor-specific renal arterial supply, prediction of collecting system opening, and prediction of postoperative renal function. They concluded that this imaging technique might suggest to the surgeons the best adjusted surgical margin size and arterial clamping point by virtual simulation [15]. Ueno et al. demonstrated that segmentation methods showed the prediction of urinary tract opening and the position of the opening as useful preoperative information [25]. Isotani et al. demonstrated in the video report in 2017, they showed the 3D-virtual surgical simulation and surgical assistance allowed for preserving renal function by minimizing the excision margin and limiting the ischemic area [16]. In 2016, Bernhard et al. reported their clinical experience with the 3D printing kidney models made from 3D-virtual surgical simulation with segmentation technology [26]. They demonstrated that this imaging technology also facilitate patients' pre-surgical understanding of their kidney tumor and surgery. As for the surgical outcomes, from Italy, there are some reports using the same segmentation technology. In 2018, Porpigli et al. showed that the 3D-virtual surgical simulation of the kidney with segmentation seems to promote selective ischemia to help in avoiding the global ischemia of the kidney compared to 2D CT [27]. In his report, he noted that in 90% of patients with 3D-virtual surgical simulation, the intraoperative management of the renal pedicle was performed as preoperatively planning, even though, in 39% of the group without 3D simulations group, the renal arterial pedicle management was intraoperatively changed [27].

In 2019, Porpigli et al. also showed that 3D-virtual surgical simulations were more precise than 2D standard imaging for evaluating the surgical complexity for partial nephrectomy. They showed a better perception of tumor depth and its relationships with intrarenal structures by 3D-virtual surgical simulation and resulted in predicting postoperative complications [28]. Additional supportive papers were reported by Bianchi et al. and Schiavina et al. in 2020 [22, 23]. However, even with the high-fidelity 3D simulation imaging, there was an absence of support for this imaging technology, which had a significant shortening effect on the total operation time or WIT (warm ischemic time) until 2021. Kobayashi et al. demonstrated in 2020 that the 3D surgical navigation system using the 3D-virtual surgical simulation showed preserving of renal parenchyma in robot-assisted partial nephrectomy, and it might contribute to improvement in postoperative renal function [29].

In 2021, Michiels et al. reported the significant benefit of 3D-virtual surgical simulation with segmentation in decreased warm ischemia time and reduced serious complications with the increased proportion of selective clamping. However, at the same time, they showed that the total operation time had been longer than without the 3D surgical simulation [20]. The longer operation time was due to the requirement of dissection of segmental arterial branches with risk of vascular injury. They concluded that the 3D-virtual surgical simulation and intraoperative guidance, the perioperative medical and surgical management may account for better clinical perioperative outcomes. These published articles supported that 3D-virtual surgical simulation may play an important role to refine patient counseling, surgical decision-making, and pre-and intraoperative planning for RAPN, and it helps to achieve precision surgical strategies and techniques according to the individual patient's anatomy.

4. Future development and options

Many articles suggested that by using 3D-virtual surgical simulation, the surgeon could have some benefit for Robotic partial nephrectomy. These surgical techniques, which combined with 3D-virtual surgical simulation and intra-op surgical navigation, may allow "Precision Surgery" to preserve renal function by minimizing the excision margin and limiting the ischemic area [16].

The future additional developments with 3D-virtual surgical simulation are the augmented reality (AR) in different surgical interventions [23] or registration of the 3D-virtual surgical simulation such as touch-based registration [19]. Even these some challenging articles have been reported, the accurate registration methods still have several problems or limitations to clinical usage [19]. No group has achieved that fully automated registration with noninvasive way during the current surgical RAPN workflow with quantitatively accessed registration accuracy. The future additional developments with 3D-virtual surgical Also, further areas may contain the automated segmentation method of the renal organs and incorporation of topological organ changes or tissue deformation by the human body status. Because it is known that the kidney has been moving up 10 mm cephalad and 11 mm medially in the flank position, and the respiratory motion makes the shifting the kidney in left-right, anterior-posterior, and cephalad-caudad directions.

These limitations suggested that ideally real-time registration methods to enhance the accuracy are required with endoscope data, updated with intraoperative ultrasound or touch-based registration [19].

5. Conclusion

Imaging surgery simulation in partial nephrectomy is useful for evaluating the difficulty of surgical procedures and for navigation during surgery planning and surgery, especially those using segmentation imaging technology. It is expected that such image processing technology will become more convenient and practical. In addition, image processing technology is expected to be incorporated and integrated into robot functions.

Additional video materials

Additional video materials referred to in this chapter can be downloaded at: https://bit.ly/3EDIo7Q.

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