3D Virtual Models and Augmented Reality for Robot-Assisted Partial Nephrectomy

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12.1 Introduction

Nowadays, urological surgery has been changing its prerogatives, heading towards a patient-tailored management, especially when facing malignancies [7]. This new approach aims to obtain an equal balance between oncological safety and functional results. Focusing on renal cancer and the related surgery, the maintenance of functional results covers a crucial role, since renal function is fundamental for the body homeostasis and for potential medical treatment [9, 10, 22]. Because of these

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specific characteristics, the handling of renal lesions with nephron-sparing techniques, even in case of complex tumors, became increasingly popular, also taking advantage of the technological novelties, in particular robotic-surgery [11]. In order to reach optimal oncological and functional results by creating a patient-tailored approach, the performance of image-guided surgery is crucial [5, 8].

Amongst the different technologies available, the three-dimensional (3D) image guided surgery is one of the most attractive ones, with very promising clinical application.

In this chapter we will explore the universe of 3D guided surgery, starting from the realization of the 3D models, to their application in surgical planning and navigation.

12.2 What is a 3D Model?

A 3D-model is a virtual or physical representation of the surface of an object. It can be obtained by using a dedicated software (virtual model) or it may also be physically manufactured (printed model). The operator (i.e., modeller) recreates and transforms an idea (i.e., virtual model) or a real object into a different product, using the available technologies. In the past, the first 3D-modellers were artists: sculptors and painters had the ability to shape different materials into the chosen form, using various instruments, which were the most disparate, translating their ideas (e.g., virtual models) into actual objects (i.e., printed models). The advent of the computer and informatics brought great innovations, which allowed artists and scientists to create and benefit from new techniques, changing the status quo of their respective fields. A modern example is represented by the movie industry, twisted by the advent of 3D-rendering softwares allowing to outline the human presence from the movie-set.

In the medical field, particularly in the surgical environment, the creation of 3D models represents one of the cornerstones of the so called “surgery 4.0” [20].

Each patient is unique, his/her anatomy is at the same time identical and different from the other patients, so it is mandatory to study each case with the aim to offer a tailored and personalized treatment.

It is important to underline that the correct interpretation of the information obtained from the standard preoperative 2D images (e.g., contrast-enhanced CT scan) requires a thorough anatomical knowledge and clinical experience. In addition, the mental transformation from 2 to 3D is not an easy process. Therefore, following this principle and trying to overcome these problems, 3D technology finds its role, progressively becoming an important tool in the daily clinical practice [17].

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12.3 How to Create a 3D Model?

In the framing process of the major part of urological diseases, radiological imaging such as CT or MRI, represents a fundamental step in order to plan the best treatment for each single patient. The main limit of these radiological instruments is represented by the two-dimensionality of the images, which require an accurate anatomical knowledge in order to avoid misinterpretations, in particular when the operator are young urologists with limited experience [23]. In fact, the “building in mind” process a surgeon is required to perform, needs to follow a learning curve, which takes time to be walked. As evident as it can be, 3D reconstructions offer immediate and intuitive information, more easily accessible when compared to 2D CT/MRI images: proportions and relationships between nearby organs are more understandable and the pathology itself (whether malignant or benign) can be displayed and visualized in a different fashion.

The realization of a 3D models starts from the processing of bi-dimensional images. Commonly, almost every DICOM viewers software provide, by default, a 3D reconstruction, thanks to an automatic rendering process. Unfortunatly, the quality is often poor in resolution and the model lacks many details.

Notwithstanding the quality of these models, they can add some information and details when compared to 2D images, thanks to the organs’ visualization and the display of the disease’s features.

However, surgeons cannot rely on poor quality models before performing a surgical procedure and, in order to realize better reconstructions, a new specialized figure was introduced: the bioengineer. The collaboration between surgeons and engineers has led to the creation of more satisfying models in terms of details and anatomical accuracy.

The interaction and communication between these two parts (doctors and engineers) is fundamental: engineers must understand the surgeon’s needs and vice versa, in order to create an accurate computer project.

Practically speaking, the realization of the models starts from the acquisition of bidimensional images. The most useful material is obtained by CT scan (multislice is preferred) or MRI images, which can be easily exported in DICOM format.

The image quality is fundamental, since it increases linearly with the precision of the 3D reconstruction; in order to obtain good quality models, the thickness of the single slice should not exceed 5 mm.

First of all, using DICOM images displaying softwares, the object must be analyzed, the most useful images (e.g., arterial or late phase of a CT-scan) must be selected and specific parameters (e.g., image contrast and luminosity) have to be modified and regulated in accordance with the project’s needs. This phase is named “preprocessing phase”.

Subsequently, a volume rendering is created: the software automatically generates an initial version of the 3D model, using the information included in the image voxels. A voxel is the basic volume unit, the equivalent of a pixel in a 2D system. Thanks to this rendering, the engineer can have an overall idea of the project, identifying the project’s critical issues.

Afterwards, a process called "segmentation" is performed thanks to a dedicated software. Segmentation is defined as the isolation of pixels included in regions or objects of interest (ROIs/OOIs), selected on the basis of a subjective similarity criterion (e.g., color). The best method to identify different ROIs/OOIs is called "thresholding", which is based on the selection of a specific range of a defined parameter (e.g., gray scale). After the range has been set, the software can consequently identify all the regions with the chosen characteristics and, subsequently, specific algorithms are generated, and other regions/objects are automatically discarded. This represents a fundamental step for the realization of the 3D models: in some cases, the software is not able to correctly identify and depict the different features and this process needs to be done manually. The experience of the engineer is particularly relevant at this stage, since the reconstruction must be precisely tailored, almost such as a dressmaker would do in a fashion atelier.

Once this process is completed, the project can be exported and saved in.stl (Standard Triangulation Language) format and, when needed, the operator can perform furtherly modify the rendering, using dedicated softwares. Finally, the virtual 3D model is completed (Fig. 12.1).

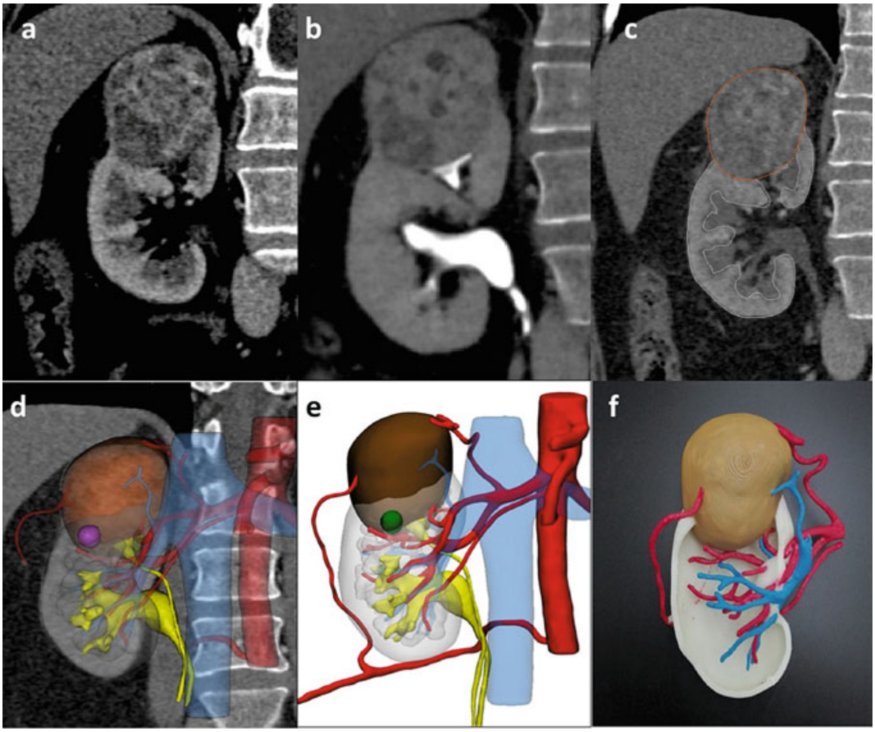

Fig. 12.1 3D model processing: **a** CT scan; **b** c.e. CT scan; **c** segmentation phase aimed to identify the different anatomical structures; **d** 3D model obtained can be overlapped to the CT images; **e** hyper-accurated 3D virtual model; **f** 3D printed model with FDM technology

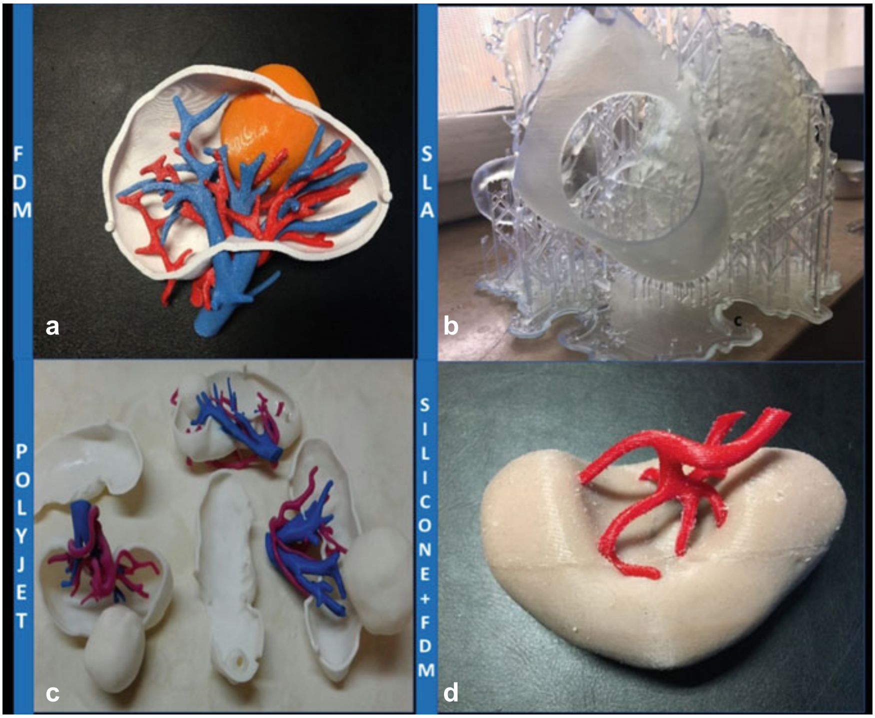

Fig. 12.2 3D printing technologies: **a** Fused Deposition Modeling (FDM); **b** Stereolitography (SLA); **c** Multi-material Plastic Jetting (Polyjet); **d** Silicone mold pouring combined with FDM printing

Once obtained, the model can be uploaded on almost any electronic devices (*see subchapter below*) for its virtual three-dimensional visualization.

Alternatively, using dedicated hardware, it can be printed using different 3D printing technologies, with different characteristics and potential applications [12, 26] (Fig. 12.2).

12.4 How to Review the 3D Models?

There are essentially two different ways to review 3D reconstructions: display them on an electronic device (virtual models) or create a physical object (printed models).

Nowadays, virtual models represent the most appealing tool amongst the two, since they are accessible from any electronic device (e.g., smartphones, tablets, laptops) and offer an intuitive experience. The chance to export.stl files in.pdf format allows to easily send 3D models via email or via dedicated platforms (e.g., MyMedics–Medics Srl©), allowing a joint teamwork between different people in different hospitals.

Table 12.1 Summary of the different display systems for 3D virtual models

	Vision	Environment	Consultation	Clinical application
2D flat screen	2D	Real + Virtual monitor	2D monitor (tablet, smartphone)	Surgical planning
Mixed reality	3D	Virtual + Real	Head mounted display (i.e., Hololens)	Surgical planning and surgical navigation
Virtual reality	3D	Virtual	Immersive head mounted display (i.e., Oculus Rift)	Surgical planning and training
Augmented reality	2D/3D	Virtual + Real	Robotic console	Surgical navigation and training

Fig. 12.3 2D flat screen visualization of the 3D models during cognitive robotic partial nephrectomy

3D models can be displayed variably, depending by the surgeon needs and by the hardware's availability (Table 12.1):

- 2D screen (e.g., TV, tablet): the virtual model is displayed on a 2D surface and can be zoomed, tilted, rotated and translated according to the operator's needs, using a touch screen or a joystick/mouse.
- The model can also be variably modified (e.g., transparency, colors), compatibly with the software used. In this setting, the absence of 3D vision represents the main limitation (Fig. 12.3).

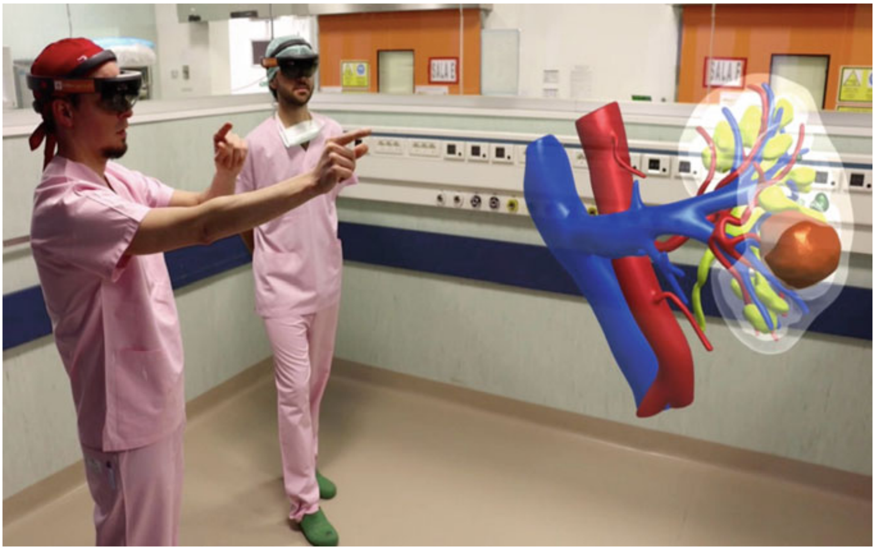

Fig. 12.4 3D mixed reality visualization of the 3D virtual model for preoperative surgical planning

- Mixed Reality (MR): in this setting, the use of dedicated devices (e.g., head mounted displays, such as HoloLens®) allows the superimposition of virtual elements to live images. Thanks to this instruments, three-dimensional virtual images are merged with the real environment. This technique finds its principal application in during preoperative planning, allowing the operator to physically walk around the model and to interact with it through gestures. These devices are usually equipped with broadcasting technology, so that an audience can experience what the operator sees through the lenses, live (Fig. 12.4).
- Virtual reality (VR): this technology allows the operator, using dedicated visors, to interact with a fully virtual environment. In this setting, surgeons are immersed into a totally virtual reality where they have the chance to interoperate, through preset gestures, with the 3D model; it must be emphasized that this technology totally excludes the real environment from the operator's view. VR can alternatively be enjoyed using virtual simulators [e.g., for robotic surgery: dV-Trainer (Mimic, Seattle, WA, USA), da Vinci Skills Simulator (Intuitive Surgical, Sunnyvale, CA, USA)]: these machines serve as training devices for surgeons of different levels of experience, offering the possibility to practice particular tasks (e.g., suturing, moving objects) or entire procedures (e.g., partial nephrectomy, radical prostatectomy) while being immersed in a fully virtual environment. The most realistic devices also offer a haptic feedback, resembling the actual intraoperative scenario.
- Augmented Reality (AR): AR can be defined as the overlay of digitally created content into the user's real-world environment with the aim of enhancing

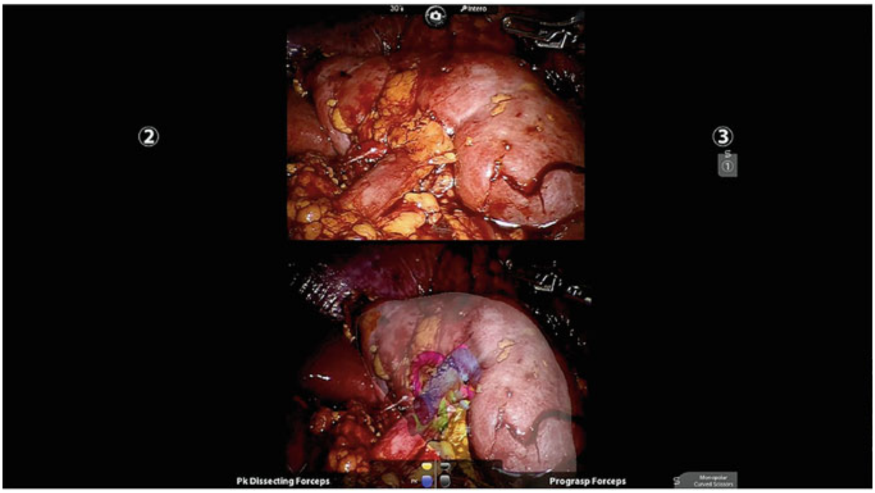

Fig. 12.5 3D augmented reality image was overlapped to in-vivo anatomy during robotic partial nephrectomy

real-word features. This technique finds its perfect application during surgical procedures, since the surgeon can overlap virtual reconstruction to the intra-operative images, adding important information during the surgical procedure (e.g., tumor margins, vascular anatomy) (Fig. 12.5).

In a recently published survey [2], all of the aforementioned methods were analyzed, and surgeons of different experience level were asked to evaluate each modality applied to different fields of interest. The most appealing technology for intraoperative guidance and training for kidney surgery was the AR technology, (58.3 and 40%), whilst during surgical planning and patient counselling, the use of HoloLens device and printed models were rated as the most effective in 60 and 61.8% of the cases, respectively. Another interesting point was that, amongst the interviewers, a poor knowledge of 3D printing costs and production times was identified.

12.5 Applications of 3D Models for Robotic Partial Nephrectomy

12.5.1 Patient Counselling

Patient counselling covers a fundamental role in the reaching of a globally successful medical act, but the communication can sometimes be tricky and challenging, since the surgeon must often face limits given by the patient's scholarship and socio-cultural extraction. Images, on the opposite, represent a straightforward and intuitive tool, easy to understand, with the power to communicate an idea in a blink of an eye.

3D models (whether virtual or printed) offer a precise and comprehensive anatomical representation of both the organ/s and lesion/s in exam, therefore they can be used to provide patients with a more immediate visualization and comprehension of their pathology.

As reported by Porpiglia et al. [11] and Checcucci et al. [16], patients and surgeons find very interesting and useful the use of 3D models, whether virtual or printed. During the 2017 Edition of Techno Urology Meeting (TUM) held in San Luigi Gonzaga Hospital (TO), specific questionnaires were administered to patients and operators. The results were satisfying both from the surgeon's and patient's point of view.

In a work by Atalay et al. [6], the importance of 3D models in the preoperative phase was highlighted: the author, by administering questionnaires to patients, showed how the overall comprehension of the anatomy, disease, treatment and related complications was improved up to 64% when compared to baseline tests. This work proved once again the great communicative power of 3D models.

Despite the higher costs of 3D printed models respect to virtual counterpart, this kind of fruition seems to be the most appreciated by the patients [2].

12.5.2 Surgical Training

Surgical training and simulation probably represent the most attractive field of application of the 3D modelling technology [13, 14] according to epidemiological studies, in fact, in the US more than 400,000 deaths by year due to medical errors have been reported and part of these unfortunate cases are determined by surgical errors [9]. The classic Halstedian model, based on the "see one, do one, teach one" paradigm must be overcome in favor of new and safe approach to learn surgical techniques. Furthermore, in order to standardize the evaluation of trainees, instruments based on virtual exercises were created: in case of robot-assisted surgery, the most known evaluating instrument is represented by the "Global Evaluative Assessment of Robotic Skills (GEARS)" [21]. By assessing six different domains (depth perception, bimanual dexterity, efficiency, autonomy, force sensitivity and robotic control), the experimenters were able to validate this tool, which has also been integrated by several institutions as a part of the curriculum.

Considering robotic-surgery simulators, the most popular and commercially available machines are the da Vinci Skills simulator (dVSS; Intuitive Surgical, Sunnyvale, CA, USA), the Mimic dV-Trainer (Mimic Technologies, Inc, Seattle, WA, USA), the Robotic Surgical Simulator (RoSS; Simulated Surgical Systems, Buffalo, NY, USA), SimSurgery Educational Platform (SEP, SimSurgery, Norway) and RobotiX Mentor (Simbionix USA Inc., Cleveland, OH). The da Vinci Skills simulator is the only platform which is based on the actual Da Vinci surgical console, simulating the use of the actual machinery. Thanks to all the aforementioned platforms, trainees can perform basic surgical skills exercises (e.g., suturing) or entire procedures (e.g., robot-assisted radical prostatectomy, RARP) accordingly to their experience, immersed in a fully virtual 3D environment. The technical differences between the different platforms and their effectiveness during training represent a topic of interest, since it is fundamental for the acquired skills to be actually useful in a real environment. All the platforms are validated, demonstrated to offer an optimal experience for trainees and their use was significantly associated to surgical skills improvement [12].

Portelli et al. published a meta-analysis concerning the impact of virtual training on laparoscopic and robotic surgery, including 24 RCTs (Randomized Controlled Trials). The Authors analyzed different parameters, such as time, path length, instrument and tissue handling and technical skills scoring, including different simulators. The final results proved that the use of virtual training improves efficiency in terms of surgical practice but also increases the quality of the surgical act itself, reducing the error rates and improving tissue handling [29].

12.5.3 Surgical Planning

The most important crossroad in the path of surgeons and, consequently, patients is represented by the treatment indication. When deciding how to approach complex diseases, the surgeon must find the perfect balance between personal experience and international guidelines and recommendations and, when necessary, discussing the case in a multidisciplinary setting, in order to take the best decisions for the patient. In this scenario, 3D reconstructions can be very important, since surgeons can gather together and discuss the clinical case, choosing the best treatment (e.g., minimally invasive vs open surgery) and the most suitable surgical approach, according to the patient's and tumor's characteristics [25].

In their work, Porpiglia et al. realized hyper accuracy three-dimensional (HA3D™) reconstructions, allowing a clear visualization of the vascular anatomy and of the intraparenchymal vessels supplying the tumor. Thanks to this precise instrument and to dedicated algorithms, it was possible to simulate the selective clamping phase during partial nephrectomy and to highlight the corresponding rate of ischemized parenchyma. This instrument revealed to be particularly useful, proving to be effective in avoiding global ischemia of the kidney [27] (Fig. 12.6).

These findings were later confirmed by a RCT demonstrating that patients treated with the aid 3-D models had reduced operative time, estimated blood loss, clamp time, and length of hospital stay [30].

3D virtual models, as previously described, can be visualized as holograms in a mixed reality setting. Antonelli et al. [4] developed a mixed-reality tool using the zSpace workstation, a Windows-based laptop connected to a stereoscopic screen displaying virtual objects. This station was designed specifically for a mixed-reality experience, giving the chance to visualize a simulation environment over

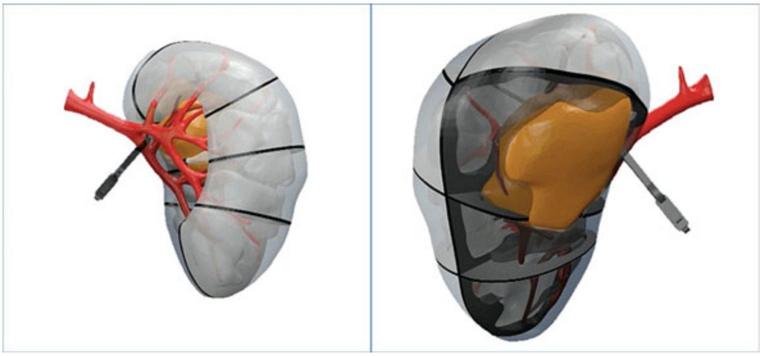

Fig. 12.6 Thanks to the 3D virtual model is possible to visualize the vessels feeding the tumour and respective rate of vascularized parenchyma; then a selective clamping can be planned

the real one. Thanks to this experience, the Authors concluded that mixed reality could improve preoperative planning for partial nephrectomy, since it provides higher quality details when compared to a computer tomography scan.

The mixed realty setting was also evaluated in another work by Checcucci et al., which focused on the high-resolution 3D perception of the organ anatomy offered by this technology and on the possibility to virtually interact with the model. Using HoloLens device, several surgeons had the chance to enjoy 3D reconstructions of complex clinical cases, displayed as 3D models "floating" in space [16]. The interviewed surgeons gave a positive feedback both for surgical planning (scored 8/10) and anatomical accuracy (9/10) on 1–10 Likert Scale. Moreover, the potential role of this technology in surgical planning and in the understanding of surgical complexity was highlighted. The impact of this technology on the decision making process was furtherly investigated by asking surgeons about the best surgical approach for each analysed clinical case: after a firsthand experience with HoloLens and MR, 64.4% and 44.4% of the surgeons changed their clamping and resection approach, respectively—ompared to CT image visualization only—in favour of a more selective one.

12.6 Surgical Navigation

Considering the increasing number of works published, only few and exploratory clinical studies have focused on the application of AR during partial nephrectomy [19].

In 2009 Su et al. [32] developed a markerless intraoperatory tracking system based on preoperatory CT images, performing an AR real-time stereo-endoscopic robot-assisted nephron sparing procedure. After calibrating the system intraoperatively, the 3D-to-3D registration was performed, and an error between the superimposed images and the real surgical field of only 1 mm was recorded.

An alternative technique was developed by Nostrati et al. [24] for the localization of visible and hidden structures, during endoscopic procedures. During a challenging robotic nephron-sparing procedures, thanks to their specifically developed method, the intraoperative accuracy of the surgical act was improved by 45% compared to standard techniques. In this specific case, the procedure was helped by the vascular pulsation cues registered using dedicated instruments [1].

In 2018, Wake et al. published an article, describing the step-by-step creation of 3D printed and AR kidney models with Unity® software, used during robotic nephron sparing surgery. These models were successively deployed to Microsoft's HoloLens® system. 3D models and AR were used preoperatively and intraoperatively to assist the surgeon. Conclusions assessed that the use of AR 3D models is safe, feasible and that it has an impact on the surgeon's decision-making process, without significant changes in the procedure's outcome [3].

In 2017 Singla et al. [31] created an AR guidance system applied during robotic nephron-sparing procedures' simulations, using ultrasonography for lesion tracking during. The registered error was around 1 mm, and the authors could consequently assess that the tested system could significantly reduce the excised volume of peritumoral healthy tissue during surgery (30.6 vs. 17.5 cm^3).

A pioneering experience was published by Porpiglia et al. [27, 28]. The Authors merged hyper-accuracy models (HA3D™) with the DaVinci software using Tile-Pro® and tested their use during partial nephrectomy. Concerning selective ischemia, AR guidance proved to be as valid as the cognitive guidance while offering the surgeon the chance to stay constantly focused on the surgical field, avoiding distraction errors. This preliminary experience implied the use of rigid 3D virtual models, unsuitable to simulate intraoperative tissue deformations. For this reason, the same group, collaborating with the engineers of *Politecnico* of Turin, consequently developed a dedicated software, introducing elastic AR. This system proved to be particularly useful during the identification and resection of hidden, endophytic tumors, especially when they were located in the posterior face of the kidney. During the procedure, in order to prove the 3D-overlapping accuracy, endoscopic ultrasonography was used, showing a perfect match between the virtual model and the lesion. Moreover, the AR images allowed to visualize intraparenchymal structures, such as vessels and calyxes, invisible with the aid of ultrasound only [28] (Fig. 12.7).

However, at current times, AR still remains a newborn and emerging technology with consequent limitations that need to be overcome [15]. The major limitation is represented by the manual overlapping process, performed by an expert assistant who needs to help the operator during the procedure. To overcome this limit, two main strategies have been theorized. The first one implies the identification of endoscopic landmarks, which can be consequently detected by the AR system [4, 24]. The second strategy, more challenging and expensive, involves a markerless approach.

Again, the group directed by professor Porpiglia, firstly start to explore this innovative approach [3] Thanks to a constant collaboration with the engineers, they created an algorithm-based computer vision dedicated software, with the objective

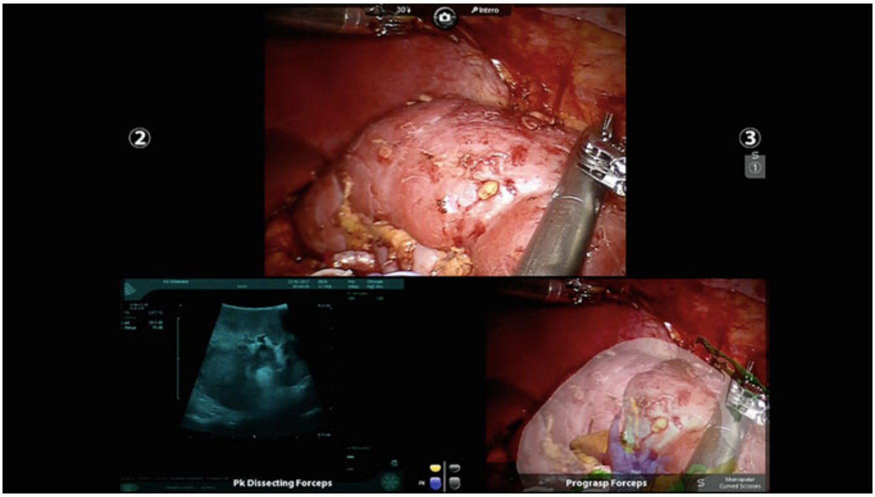

Fig. 12.7 3D augmented reality images perfectly correspond to the real time ultrasound ones

to automatize 3D virtual and endoscopic images co-registration. In particular, by leveraging the enhanced vision provided by indocyanine green (ICG), the software allowed a precise intraoperative kidney identification and a consequent automatic overlap of the 3D mesh with live intraoperative images was successfully performed (Fig. 12.8). In a pilot study, ten patients were enrolled: in all the cases, the automatic tracking was successful, allowing to perform an enucleoresection of the lesion without damaging the pseudocapsule and avoiding the occurrence of positive surgical margins.

Notwithstanding these encouraging findings, this approach was not devoid of limitations: in fact, when the kidney is rotated in order to approach posterior lesions, the shape of the organ changes dramatically, and the software is therefore unable to overlap the images. To overcome this problem, it will probably be essential the development of artificial intelligence with deep learning algorithms [18, 19], which will train the software to recognize the kidney's features and texture, reaching a more precise and stable automatic tracking during the whole procedure.

12.7 Conclusions

In an even more tailored surgery era, the image guided surgery plays a fundamental role especially during complex procedures such as partial nephrectomy. Nowadays, a paradigm shift is happening thanks to the advent of 3D models. The possibility to visualize the patient's specific anatomy three-dimensionally offers an unprecedent comprehension of the surgical complexity with a subsequent more patient-specific surgical planning. Moreover, by using augmented reality systems, these virtual 3D reconstructions can be the virtual eyes of the surgeon guiding him during the entire procedure.

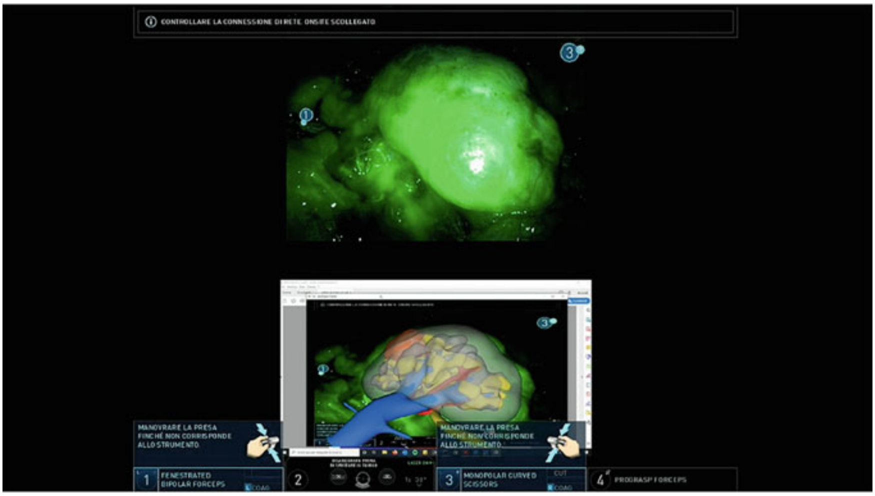

Fig. 12.8 Thanks the enhanced vision provided by indocyanine green (ICG) the computer-vision based software was able to recognize the kidney shape and automatically anchor the 3D virtual images of the kidney

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