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Pushing the Boundaries in Robot—Assisted Partial Nephrectomy for Renal Cancer

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Renal cell carcinoma (RCC) incidence increases worldwide and it is highest in developed countries. Due to expanded use of routine imaging for many disorders, nowadays RCC is usually diagnosed as an incidentaloma on abdominal imaging. This has also caused a disease stage migration with average tumour size at diagnosis decreasing over the years [16].

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Therefore, urologists are focusing on strategies to minimize the impact of therapy in terms of overall morbidity and renal function, while maintaining optimal oncological outcome. Minimal-invasive surgery is increasingly adopted to reduce short-term morbidity and allow earlier convalescence. Cancer-specific survival of T1-2 N0M0 RCC is excellent, with cancer specific survival exceeding 92% while chronic kidney disease (CKD) is associated with poor survival [34]. This led to nephron-sparing surgery (NSS) being increasingly performed instead of radical nephrectomy to optimize long-term renal function. European Association of Urology (EAU) guidelines indicate a partial nephrectomy (PN) is indicated for all T1 tumours and it should be considered for T2 tumours, especially in patients with a solitary kidney, bilateral tumours or CKD [35]. A lot of tertiary referral centres in developed countries are currently performing robot-assisted partial nephrectomy (RAPN) as the standard therapy for most of their patients with localized RCC.

A "traditional" RAPN includes the following surgical steps:

1. Development of pneumoperitoneum, placement of trocars and robot docking.
2. Reflecting of the ascending colon and duodenum and mobilization of the liver for right-sided tumours; reflecting of the descending colon and mobilization of pancreas tail and spleen for left-sided tumours.
3. Dissection of the renal hilum with identification of the renal artery (and possibly extra branches).
4. Dissection of the tumour and surrounding renal capsula.
5. Renal artery clamping (warm ischemia).
6. Tumour resection.
7. Renorraphy: classically a separate inner and outer renorraphy.
8. Unclamping and control of hemostasis.
9. Closure of Gerota's fascia, specimen extraction and closure of the abdominal wounds.

Increased experience with robotic surgery, technological improvements, and better awareness of RCC's biological behavior are allowing even more advanced RCC cases to be safely treated with RAPN. As this is an evolving field, this chapter highlights some of these contemporary evolutions. We will focus on preoperative planning using 3D models, different techniques for hilar control and different tumour resection strategies.

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6.1 Pre-operative Planning with 3D Models

An accurate surgical planning for renal cancer surgery is mandatory in order to achieve the best surgical outcomes. A comprehensive evaluation of kidney tumours is non-trivial, as tumour size, location and the relationship to the collecting system and the vascular system have to be taken into account. In order to facilitate this process, several nephrometry scores have been implemented in clinical practice over the last ten years, of which PADUA and RENAL are the most widely used [21, 33]. All current nephrometry scores have been developed, validated and calculated using bidimensional imaging. As a consequence, the surgeon is required to create a three-dimensional mental image starting by the observation of two-dimensional images in the three spatial axes (axial, coronal and sagittal), with suboptimal results [50]. Especially when dealing with complex kidney tumours, where bidimensional imaging has been suggested to provide inadequate assessment [59].

Thanks to its ability to overcome some limitations of established imaging techniques [14], the use of 3D technology has widely spread in the urological community since its first use in 2012 [65]. Moreover, 3D reconstructions have been proven to have a stronger correlation with excised renal tumour, in terms of both morphology and volume, when compared with conventional imaging [67].

Available studies on the usefulness of 3D reconstruction report on rather small patient series, which remains a bottleneck in acquiring clear evidence. One key aspect several authors investigated, is the impact on indication shift from radical to partial nephrectomy using 3D models, both virtual and printed. Wake et al. reported a change of 30–50% after visualization of a 3D printed kidney model by the surgeon [68]. Bertolo et al., evaluated the role of 3D planning in highly complex renal tumours, either regarding the size of the tumour or other anatomical characteristics. Of the urologists involved, and regardless of their experience, 25% changed their indication after reviewing the 3D model in favor of PN [9].

In order to overcome the limits of conventional imaging in nephrometry scoring, Porpiglia et al. suggested the use of 3D reconstruction for the assessment of nephrometry scores [49]. Using three-dimensional models, all cases experienced a significant change in the score assigned to renal sinus involvement, urinary collecting system invasion and exophytic rate, while up to 50% of the cases had a downgrade in the PADUA and RENAL risk group. In summary, current evidence suggest that 3D models provide a more accurate overall perspective on renal cancer surgical planning, broadening the indication for nephron sparing surgery. Moreover, these findings may imply a shift in current research trends, moving the focus from “which is the most accurate nephrometry score” to “which is the best imaging tool for tumour complexity evaluation”.

While 3D models can help provide anatomical insights and broaden the candidate selection for nephron sparing surgery, other studies have shown that use of 3D models may also lead to reduced operative time, estimated blood loss, clamping time and length of hospital stay [38, 58].

Also the arterial clamping strategy is shown to be altered, resulting in a higher rates of selective and super-selective clamping without increasing intraoperative and postoperative complications [11, 56]. Concerning clinical outcomes of the use of 3D models in renal surgery, the largest retrospective analysis of 3D guided RAPN to date shows significantly higher trifecta achievement rate, lower perioperative transfusion rates and a shorter length of stay [38]. As such, 3D models are expected to further impact intra-, and post-operative outcomes.

6.2 Hilum Control

In a “traditional” PN, renal artery clamping is a standard step just before tumour resection in order to achieve a bloodless resection field. This has many advantages: it allows precise tumour resection without perforation of the tumour (pseudo)capsula, allows minimal resection of normal renal parenchyma and minimizes blood loss. Although prolonged ischemia is a risk factor for acute kidney injury and CKD, the most important determinators of postoperative kidney function are the pre-operative kidney function and the remaining vascularized renal parenchyma [63]. Recent insights learned the human kidney is more tolerable to prolonged ischemia and the concept of 20 to 30 min of “safe ischemia time” is being challenged in patients with bilateral healthy kidneys. Nevertheless, renal ischemia is one of the factors that is surgically modifiable and therefore a lot of effort has been put in developing strategies to minimize healthy renal parenchyma ischemia: off-clamp resection, early unclamping, superselective clamping or establishment of cold ischemia.

6.2.1 Off-Clamp Resection

In an off-clamp resection, the renal hilum is never clamped and all renal parenchyma (and the tumour) remain vascularized during the procedure. For safety, the renal artery is isolated, so it can be clamped in case of excessive bleeding.

Retrospective observational studies comparing on- and off-clamp RAPN demonstrated conflicting results, probably due to selection bias [30, 54]. A meta-analysis in 2019 reported higher blood loss for off-clamp RAPN (mean difference + 47 mL), but similar transfusion rates, complications, and positive surgical margins. Renal function was superior for the off-clamp group both in the short-term change in estimated glomerular filtration rate (GFR; mean difference 7%) and long term (mean difference 4%) [13]. However, the quality of such evidence is very low.

Therefore, two randomized controlled trials (RCTs) analyzed the effect of renal artery clamping versus off-clamp PN on renal function. The recent CLOCK trial randomized 324 patients from several Italian centres with bilateral kidneys, normal kidney function (GFR >60) and a solitary kidney tumour with a RENAL score ≤ 10 to receive either an on-clamp or an off-clamp RAPN [5]. In the “off-clamp” group 43% of patients were crossed over to on-clamp because of excessive bleeding (34%) or because the surgeon desired ischemia ‘due to high complexity of the tumour’ (9%). No significant differences were seen in terms of estimated blood loss, transfusion rates and postoperative complications [4]. Warm ischemia time (WIT) was limited (median 14 min, interquartile range [IQR] 11–18). No significant difference in postoperative kidney function at 6 months was seen (median -6.2 ml/min [IQR -18 – 0.5] on-clamp versus −5.1 ml/min [IQR -14 – 0.1] off-clamp), nor at 12, 18 and 24 months, both in the intention-to-treat analysis and the per protocol analysis [5].

Similarly, Anderson et al. randomized 71 patients in a single-surgeon RCT between on- and off-clamp RAPN and found no significant difference in 3-month postoperative GFR [3].

It seems that in most patients considered for RAPN, on- or off-clamp strategies have limited impact on clinical outcome. However, this might not be the case for patients with a solitary kidney, pre-existing CKD or more complex tumours with expected longer ischemia time.

6.2.2 Early Unclamping

In early unclamping, perfusion is restored not after double-layer renorraphy but already after internal renorraphy [6]. Some observational series demonstrated a reduction in WIT with a median 5.6 min in RAPN [48]. A meta-analysis of a handful observational series on laparoscopic and robotic PN calculated an increase in mean blood loss of only 37 mL after early unclamping with no difference in transfusion rates or complications [14]. One study assessed postoperative renal function and found no significant difference [48]. When possible, early unclamping is safe, diminishes WIT and provides the surgeon with feedback on hemostasis after internal renorraphy.

6.2.3 Superselective Clamping = "zero Ischemia"

Selective arterial clamping can avoid unnecessary ischemia to healthy renal parenchyma on one side while minimizing the risk of complications such as bleeding on the other side. In superselective clamping (sometimes referred to as the "zero-ischemia" technique), only the tumour-feeding renal vessels are temporarily clamped, to further minimize ischemic damage to healthy tissue and approximate the off-clamp situation. In this technique dating back to 2011 [23], tertiary or higher order branches of the renal artery are dissected. However, the main enigma here remains how to determine up front which vessels need to be dissected/clamped and if this dissection is worth the accruing risks of bleeding and increased operative time. Gill et al. who originally proposed this technique have been using 3D models since 2012 to facilitate this decision [24]. Near-infrared imaging and indocyanine green (ICG) administration was also used in later studies to determine if the clamping was successful at the kidney surface level before starting resection. This showed that a purely cognitive clamping-position estimation does not always establish an avascular resection [12]. Indeed, the clamping strategy is solely based on the surgeon's assessment of which vessels are perfusing the tumour. In lateral rim tumours for instance, vessels are not always connected to the tumour region due to limits in CT imaging resolution. Thus, perfusion needs to be roughly estimated by a 3D 'cognitive region fusion' of nearby vessels.

The first simulation of perfusion regions in 3D renders can be traced back to 2018 [52]. However, no details on the perfusion algorithm or validation are provided and different perfusion zones are separated by straight planes. Each vessel is estimated to perfuse the same perfusion volume with a subsequent linear percentage split (Fig. 6.1).

Figure 6.1a shows how parenchymal percentages can be estimated. Figure 6.1b shows this on a specific case. Figure 6.1c A planar cut is made to estimate which part we need to clamp. Figure 6.1d Looking at this cut, we would estimate the healthy parenchyma which is being clamped to be around 42% (16.6% + 16.6% + 8.3%). It is clear that precise estimation of ischemic volumes is unlikely. Ischemic volumes appear non-physiologic and benefits of a certain clamping strategy are hard to estimate.

More recently, newer perfusion algorithms are demonstrated and validated, based on mathematical models which include several patient-specific arterial features [19]. These models automatically predict ischemic parenchyma and tumour volume percentages and as such objectively inform the surgeon of the risk/benefit ratio in clamping extra vessels (Fig. 6.2).

Figure 6.2: Nearest neighbors approach taking into account arterial path and 3th generation vessels. Fig A. Virtual Model. Fig B–D: Virtual Clamping with ischemic zones indicated in green. Fig B. Clamping of artery headed towards lower pole—anterior view. In this specific case, clamping the inferior artery theoretically

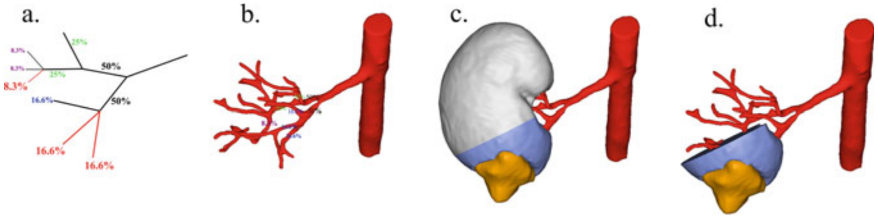

Fig. 6.1 Cognitive estimation of clamped renal volume for partial clamping

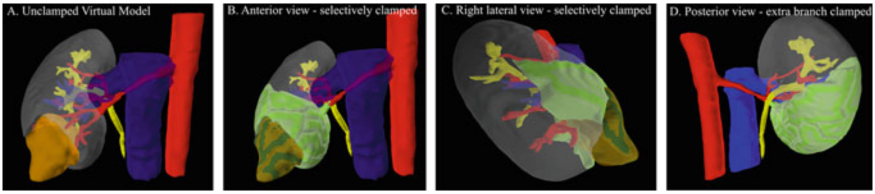

Fig. 6.2 3D perfusion model

results in 77% tumour ischemia and 16% healthy parenchyma clamping. Anterior view looks to be indicating a fully ischemic tumour. Fig C. However, right lateral view reveals the tumour is most likely also perfused by a posterior branch. Fig D. Posterior view when clamping this extra branch, just outside the parenchyma, result in 100% ischemic tumour, however with 36% additional healthy ischemic volume. This approach allows for a more informed clamping strategy.

As tumours are not seldom perfused by several branches, this type of perfusion model lets the surgeon balance off the benefit of encountering a small hemorrhage in certain areas compared to clamping a larger volume of healthy parenchyma. It also informs the surgeon where such a hemorrhage is to be expected or where bloodless enucleation can be started.

6.2.4 Cold Ischemia

In patients were long ischemia times (>30 min) are expected, cold ischemia may limit renal parenchyma damage. Several techniques exist to cool the kidney. In open PN, ice slush can be placed around the kidney. However, in minimal-invasive surgery this is more complex and therefore has not been widely adopted. For laparoscopic PN, cold saline surface irrigation [31], retrograde cooling through the ureter [17] and intra-arterial cold perfusion [29] have been performed. There are no studies comparing these different cooling techniques in terms of kidney temperature and postoperative renal function in minimal invasive surgery. In 1980 Marberger et al. analyzed 95 patient who underwent hypothermic nephrolithotomy. Sixty-three kidneys were cooled by transarterial cold perfusion and 39 were cooled by topical ice slush. Postoperative kidney function decreased less in the perfused group (−19.4% at 2 weeks; −7.9% at 6 months) than in the topical group (−30.3% at 2 weeks; −29.8% at 6 months) [36]. Possibly, intra-arterial cold perfusion delivers a more homogeneous renal parenchyma cooling compared to topical cooling.

A recent systematic review and meta-analysis found no significant difference between cold and warm ischemia in terms of blood loss, surgical margins and postoperative drop in kidney function following PN. However, the number of included studies and patients was low, as was the level of evidence (Oxford level of evidence 4) [25].

Practical considerations and lack of an 'optimal' cooling technique hampered the adoption of cold ischemia in RAPN thus far. It remains an option, however, before autotransplantation and bench surgery or even radical nephrectomy in patients with solitary kidney or CKD with very complex tumours.

In summary, two systematic reviews and meta-analyses in 2019 demonstrated that no ischemia technique (off-clamp, on-clamp, superselective clamping or cold ischemia) is superior over the other in patients with bilateral healthy kidneys. A surgeon must balance between acceptable ischemia time, limited ischemia zone and operative risk and duration, while maintaining maximal oncological control. Additional prudence is required in patients with solitary kidneys or CKD. 3D models can aid in choosing the best strategy.

6.3 Tumour Resection Strategy

Resection strategies and techniques for PN are still object of great interest and debate among urological surgeons and researchers. In fact, the most recent EAU and American Urology Association (AUA) guidelines recommend PN as the gold-standard treatment for patients with localized T1 renal tumours [35], making the technique for tumour excision of great value to achieve the goals of oncologic efficacy, maximal renal function preservation and perioperative safety.

The debate over the merits and potential limitations of different resection strategies and techniques for RAPN has been reinforced by several recent studies. In particular, as the amount of functional parenchymal mass preserved during PN has been shown to be one of the strongest modifiable predictors of functional recovery after surgery (provided that extended warm ischemia time is avoided) [37], some authors have argued that tumour enucleation (TE) may have distinct benefits over "standard" PN (i.e. enucleoresection) without compromising oncologic safety [26]. Among these, TE may allow surgeons to excise the tumour with optimal visualization of its contours (resecting only a microscopic amount of healthy renal tissue [40] and thus reducing the risk of positive surgical margins), while keeping the risk of damages to the urinary collecting system and/or renal sinus to a minimum, especially in case of anatomically complex, hilar renal masses [26]. Importantly, TE may also sponsor a "nephron-sparing" renorrhaphy, especially during RAPN. Indeed, nephron-sparing tumour excision (minimal-margin PN or TE), following a relatively avascular dissection plane, facilitates anatomical nephron-sparing renal reconstruction; this concept is of utmost importance for highly complex and/or hilar tumours, with potential additional benefits in terms of renal function preservation and minimization of perioperative complications [10].

For several years the standard surgical technique PN was the excision of a 1-cm peritumoural tissue to achieve negative margins. This surgical strategy was not without risks, considering the amount of vascularized parenchymal volume resected, the potential urinary collecting system injuries, and the higher risk of prolonged warm ischemia time (WIT) [66].

Interestingly, while originally preferred for nephron-sparing surgery in case of hereditary kidney tumours and for imperative indications, TE has gradually been applied in elective settings for both T1a and T1b/T2 tumours by an increasing number of surgeons [41].

From a pathologic standpoint, tumour enucleation takes advantage of the presence of a distinct fibrous pseudocapsula in most renal tumours as well as of the histologic changes at the tumour-parenchyma interface [44]. This directly translates into the "surgical concept" of TE, which relies on the excision of the tumour predominantly by blunt dissection following the natural cleavage plane between the peritumoural pseudocapsula and the renal parenchyma (without removing a visible rim of healthy renal tissue). In this regard, several studies have shown that the incidence of positive surgical margins after TE is consistently very low, making TE at least non-inferior to standard PN in this regard [43].

A recent study found that, in experienced hands, robotic TE allows to excise the tumour with negative surgical margins even in case of pseudocapsula infiltration, by providing a “microscopic” layer of healthy renal tissue beyond the peritumoural pseudocapsula [39], with no recurrences found in the enucleation bed at a long-term follow-up. As such, robotic TE is oncologically safe and has the potential to meet further essential requirements for PN, such as to widen the indications to tumours with the most unfavourable nephrometry scores while maintaining a low complication rate and maximizing the volume of vascularized parenchyma preserved [44] (Figs. 6.3 and 6.4).

The cornerstones of robotic tumour enucleation are shown in detail at: https://surgeryinmotion-school.org/v/563/. Robotic tumour enucleation has been shown not to be a zero-margin technique but rather a microscopic- margin technique, resecting a microscopic (<1 mm) silver of healthy renal margin in most cases [39].

An anatomic resection strategy (enucleative intent) is key to allow the surgeon to clearly appreciate the tumour’s contours and excise the tumour with macroscopically negative surgical margins.

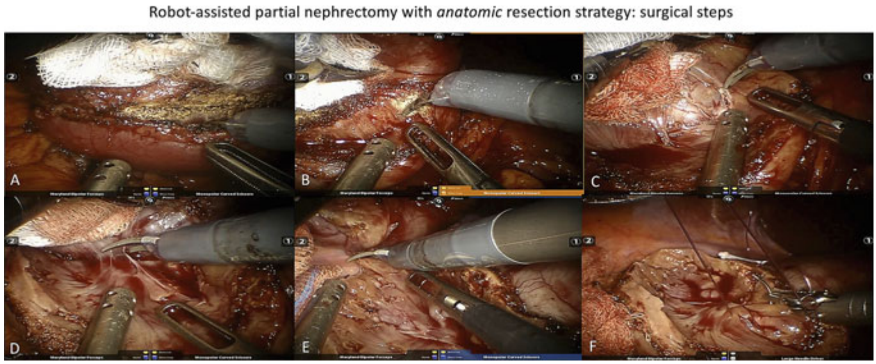
Robot-assisted partial nephrectomy with *anatomic* resection strategy: surgical steps

Fig. 6.3 Intraoperative snapshots showing the main steps of robotic tumour enucleation


Robot-assisted partial nephrectomy with *anatomic* resection strategy for tumours with venous thrombosis

Fig. 6.4 Intraoperative snapshots showing a case of robotic tumour enucleation for a small renal mass with venous thrombosis

Despite the robust evidence confirming the oncologic safety of TE during both open and robotic PN [39, 43], whether TE is ultimately safe for all patients with localized renal tumours who are eligible for nephron-sparing surgery is still debated within the Urology community [26, 42, 64]. In fact, some experts remain sceptic about the real advantages of TE, arguing that TE may lead to insignificant differences in postoperative renal function and complications as compared to standard PN, at the cost of a higher risk of tumour violation (Fig. 6.5).

Figure 6.5: Left side: distinct merits of tumour enucleation from a surgical perspective include the clear visualization of the tumour contours, the possibility to avoid positive surgical margins especially for tumours with no perfectly spherical shape (as in the figure), maximization of the amount of healthy renal parenchyma spared during RAPN and the opportunity for “nephron-sparing” renorrhaphy. Right side: a potential drawback of tumour enucleation is the risk of tumour violation, which increases the risk of true positive surgical margins (residual tumour cells in the enucleation bed).

In a recent review on the key decision-making points in patients with localized renal masses, the authors highlighted how the resection methodology during RAPN should be grounded into a careful consideration of both patients’ and tumour’s characteristics, and that a wider-margin PN (or even radical nephrectomy) may be safer for in case of tumours with an “infiltrative” tumour growth pattern (in view of a potentially more aggressive histology) [37].

The controversy over the pros and cons of TE versus standard PN is reflected in the historical evolution of EAU Guidelines recommendations. While they originally recommended the removal of a “minimal tumour-free surgical margin” to achieve oncologic efficacy, they subsequently outlined the oncologic efficacy of TE and did not provide further recommendations to guide resection strategies and techniques during open and robotic PN [35]. The same concept can be applied to the AUA Guidelines, which stressed that TE may be more beneficial in patients with familial renal cell carcinoma (RCC), multifocal disease, or severe chronic kidney disease aiming to optimize parenchymal mass preservation [15].

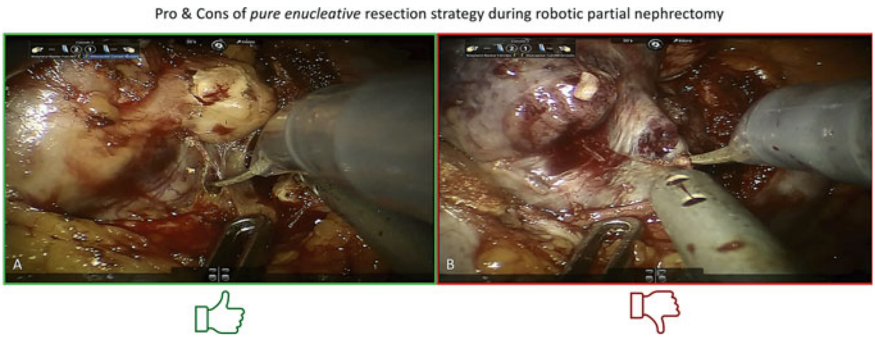

Fig. 6.5 Pros and cons of robotic tumour enucleation for localized renal masses

Unfortunately, the debate over the merits and limitations of different resection techniques has been reinforced over time by the lack of standardized reporting of resection strategies and techniques during PN. Since the initial description of nephron-sparing surgery, a number of technical strategies for excision of the tumour from normal renal parenchyma have been described, including TE, enucleoresection, and wedge resection. Yet, the descriptors of these techniques have been used interchangeably, hindering a meaningful comparison of surgical series until recently. To fill this gap, Minervini and coworkers have proposed in 2014 a standardized reporting system to communicate tumour resection technique in PN series, the Surface-Intermediate-Base (SIB) margin score [45]. This model, based on a visual analysis of the margin of healthy parenchyma scored at the superficial surface, the intermediate surface, and the base of the tumour, was soon validated from a histopathological perspective [40] and tested in a prospective, international multicentre study aiming to assess the impact of resection techniques on PN outcomes [41].

Of note, a more comprehensive model to catch the "whole picture" of tumour excision during RAPN should report not only the final resection technique (according to the SIB scoring system), but also the preoperative surgeon's intent (named "resection strategy") [42]. In fact, tumour excision during PN is a complex surgical task, and the inherent characteristics of the tumour–parenchyma interface allow definition of a constant "anatomic dissection plane" that can always be identified and bluntly developed in close vicinity to the tumour capsule, with or without the removal of a sliver of healthy renal tissue. As such, it is essential to clearly divide the concept of resection strategy (*anatomic vs non-anatomic*) from that of resection technique (*enucleation vs enucleoresection vs resection*, based on the SIB score) (Fig. 6.6).

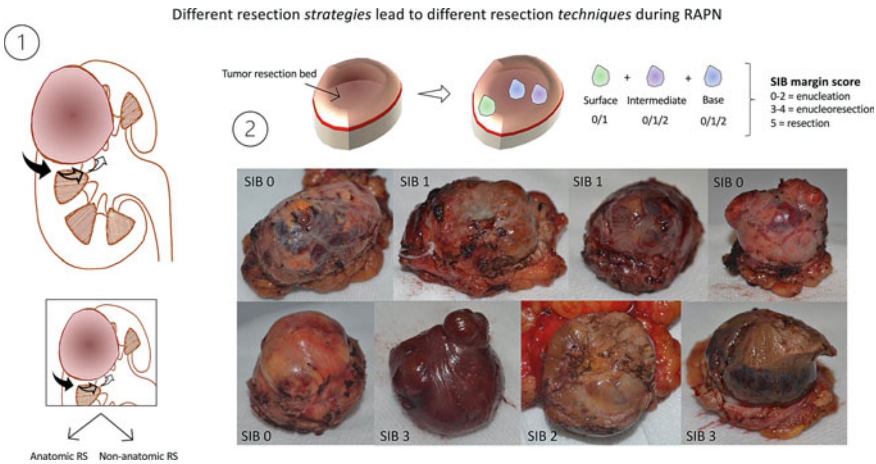

Fig. 6.6 Graphical overview of the integrated model proposed by Minervini and colleagues for standardized reporting of resection strategies and techniques during open and robotic PN [42]

A detailed overview of the SIB scoring system for standardized reporting of PN resection techniques is presented in Fig. 6.6 [45]. A step-by-step tutorial for surgeons on SIB score assignment is available at the link: https://kidney.uroonco.uroweb.org/video/sib-score-tutorial/.

Figure 6.6: (1) Resection strategy (the preoperative surgeon's intent) is classified as *anatomical* or *non-anatomical* according to the surgeon intent to excise the tumour by following the anatomical dissection plane close to the tumour or wider non-anatomical planes, removing a macroscopic layer of healthy renal tissue. (2) In contrast, the resection technique was classified as enucleation (SIB score 0–2), enucleoresection (SIB score 3 or 4) or resection (SIB score 5) according to the SIB score by visual analysis of the specimen performed by the surgeon in the operating room after PN. Details on SIB score assignment are provided in the text as well as in a step-by-step tutorial at this link: https://kidney.uroonco.uroweb.org/video/sib-score-tutorial/.

In this view, the surgeon's preoperative intent during RAPN may be reported in a spectrum ranging from a "pure enucleative" anatomic resection strategy (in this case, the aim is to follow the natural cleavage plane between the tumour and the healthy parenchyma resecting a *microscopic* amount of healthy renal tissue) to a "wedge" non-anatomic resection strategy (in this case, the aim is to excise the tumour with macroscopic margins of healthy renal tissue with no visualization of the anatomic dissection plane). Between these two extremes lie the "minimal-margin" anatomic resection strategy and the "macroscopic-margin" non-anatomic resection strategy [42].

Importantly, a prospective multicentre study has distinctly shown how resection techniques do impact on perioperative and early functional and oncologic outcomes in patients with localized renal masses [41]. In particular, the resection technique, classified after surgery according to the SIB score, was the only significant predictor of positive surgical margins and one of the strongest predictors of Clavien-Dindo grade ≥ 2 surgical complications, postoperative acute kidney injury and Trifecta achievement. This evidence reinforces the clinical relevance of standardized reporting of resection methodology during RAPN.

In summary, the goal of RAPN is complete excision of the tumour with negative margins while maximizing perioperative safety and preservation of vascularized parenchyma. To achieve this goal, individualized tailoring of the excision plane based on intraoperative assessment of the peritumoural tissue planes is needed [55]. To advance this field toward the concept of "precision RAPN", standardized reporting of excision techniques will be key for future studies to understand the impact of resection (and renorrhaphy) strategies and techniques (beyond that of surgeon's experience) on postoperative outcomes after RAPN [10, 18, 41].

6.4 Future Perspectives

6.4.1 3D Model Generation

3D models are typically reconstructed from computed tomography scans using 4 different phases: blanco, early arterial, venous and an excretory phase [11]. MRI scans can technically be used as well, although resolution is often lacking to reconstruct a useful anatomical vascular reconstruction for hilar control. A dedicated software program is to be used to reconstruct these models in a process called ‘segmentation’ as illustrated in Fig. 6.7.

This means colouring in every artery, vein, ureter, kidney and tumour that is relevant for the final model. Next, these segmentation software packages convert this planar information into a 3D model.

Segmentation software packages are available both open-source for free (e.g. 3DSlicer—http://www.slicer.org) as well as commercially. Segmentation remains a cumbersome, time-consuming, manual task. The advent of artificial intelligence is reducing the time needed for model making by automating the segmentation process. More precisely, so-called deep learning techniques are used to predict a 3D model, which can then be double checked and altered by the physician in the software packages stated above wherever needed [28].

After the generation of such a model, this file can be exported and viewed in several desktop formats. Whenever needed, these files can also be used integrally as input for 3D printing of the anatomy.

6.4.2 Virtual Models and Augmented Reality

When 3D models are viewed in desktop applications or in other purely virtual environments, we refer to them as virtual models. The term augmented reality (AR) refers to the real-time overlaying or superimposition of images captured by the intraoperative field or, more typically, peroperatively, onto a patient’s actual endoscopic video [61]. Figure 6.8 shows the difference between both approaches.

The TilePro™ technology enables the surgeon to integrate acquired imaging (3D reconstructions, CT scans, MRI images, ultrasonography) with critical visual information from the operational field. When just the virtual model is imported (Fig. 6.8a), we refer to it as a virtual model. However, a cognitive fusion still needs to take place inside the surgeon’s head. On step further (Fig. 6.8b) is to project this 3D model in the operative field. As such, these inputs may ‘augment’ the limited surgical field and intra-operative perception as associated with laparoscopic

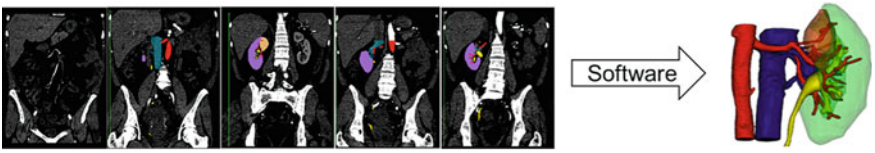

Fig. 6.7 Segmentation is the process where the 3D model maker goes through the entire CT scan using a software package and indicates relevant structures for each slice

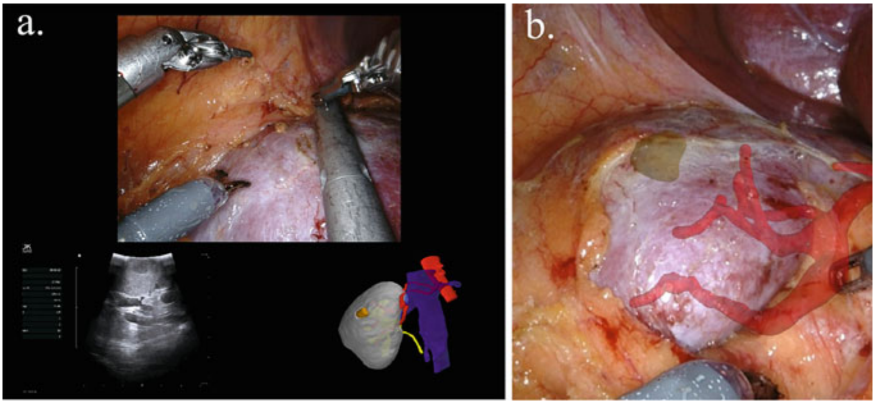

Fig. 6.8 **a**. Virtual model input using TilePro™, shows a partially endophytic tumour. Ultrasound confirms the location of the tumour. Figure 8.b. Augmented reality setting in which the same 3D model is overlapped to the endoscopic view, also showing the location of the arteries and invisible endophytic part of the tumour. It is to be noted that this is also inputted using the TilePro™ function, as the current systems do not allow to take over the main console view

surgery. In this case, the model needs to be continuously repositioned as to fit the current operative view.

Automation of this process requires image registration, which is the alignment of virtual models with the present intra-operative field. As such, image registration lies at the heart of a successful clinical implementation of AR.

AR image registration can be divided into two main categories: rigid and non-rigid. The former does not account for organ distortion as can be perceived due to repositioning of the body or renal manipulation [57, 60]. For high-precision AR navigation, non-rigid registration is required. However, the dynamic environment of the abdominal cavity makes non-rigid registration incredibly challenging, especially when approaching anatomical structures such as the renal hilum. Several deformation registrations, such as 3D splines [2], non-linear parametric models [51], elastic finite element model (FEM), and biomechanical models [27], can be employed to compensate this necessity.

Most laparoscopic AR navigation systems require so-called manual or semi-automated registration. Manual registration refers to manual alignment of virtual models with endoscopic pictures. Each time the operative view changes, the model must be manually re-aligned using a user interface. Semi-automatic registration necessitates human initial alignment before automatic follow-up. As such, manual and semi-automated registration impair the surgical flow as they require the surgeon or assistant to constantly or intermittently realign the model.

Automatic registration is facilitated by the use of extra sensors in the operative setup. Using electromagnetic or optical tracking sensors to rigidly localize the laparoscope may result in automatic registration. Using fiducials into a kidney silicon model, Teber and Kong et al. demonstrated completely automated augmented reality navigation during laparoscopic PN with great navigation accuracy [32, 62]. However, these tools do not allow the use of a deformable model and because of the intrusive character of the used markers, this approach is not suitable for clinical use [60].

To avoid the use of physical markers, Wild et al. postulated the use of fluorescent dyes, which of course require the procedure to be performed using a laparoscope capable of fluorescence imaging [69].

Further options include the use of stereoscopic laparoscopy to reconstruct the intra-abdominal organ surface to accomplishing registration. In this approach, a live 3D reconstruction is made of the intra-abdominal cavity by using both eyes of a laparoscope with 3D vision, as is the case in robotic surgery. These reconstructions, however, frequently contains insufficient feature points. Furthermore, feature detection may be hampered by several factors, such as texture-poor appearance, specular reflection, and shadows. Moreover, due to the limited endoscopic view (the angle of a laparoscope view is only 70°), only a tiny portion of the organ surface may be rebuilt. It makes automatic registration of an entire 3D anatomical model extremely difficult, necessitating manual initial alignment [8].

Finally, Bernhardt and colleagues proposed a registration algorithm that does not rely on tracking devices or markers. It identifies the location of the endoscopic camera relative to the intra-operative 3D data by incorporating the endoscope tip inside an intra-operative 3D C-arm volume [8]. However, this requires both a setup with a radiographic C-arm inside the operative room as well as the use of a three-axis accelerometer integrated into the endoscopic camera.

Summarizing, to properly incorporate AR in a clinical real-life scenario, some requirements must be fulfilled:

1. Conventional preoperative imaging must be used to easily generate 3D surgical models.
2. The 3D model must be projected onto the live intra-operative anatomy, requiring registration of the model using preferably visual cues and a deformable model.
3. Surgical instruments must be tracked, as well as any mobility of the targeted organs and their surrounding anatomies.

Even if great steps forward have been made in the last few years, we are still just at the beginning of the development of this technology.

6.5 Conclusions

RAPN is no longer a standard ‘one technique fits all’ procedure, but is continuously evolving towards precision RAPN. A surgeon should encounter every patient with a personalized strategy for hilum control and tumour resection, in order to minimize renal ischemia and maximize the remaining vascularized renal parenchyma. 3D models can aid in pre-operative planning and peroperative guidance, especially in complex cases.

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