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A Literature Review of Renal Surgical Anatomy and Surgical Strategies for Partial Nephrectomy

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Abstract

Context—A detailed understanding of renal surgical anatomy is necessary to optimize preoperative planning and operative technique and provide a basis for improved outcomes.

Objective—To evaluate the literature regarding pertinent surgical anatomy of the kidney and related structures, nephrometry scoring systems, and current surgical strategies for partial nephrectomy (PN).

Evidence acquisition—A literature review was conducted.

Evidence synthesis—Surgical renal anatomy fundamentally impacts PN surgery. The renal artery divides into anterior and posterior divisions, from which approximately five segmental terminal arteries originate. The renal veins are not terminal. Variations in the vascular and lymphatic channels are common; thus, concurrent lymphadenectomy is not routinely indicated during PN for cT1 renal masses in the setting of clinically negative lymph nodes. Renal-protocol contrast-enhanced computed tomography or magnetic resonance imaging is used for standard imaging. Anatomy-based nephrometry scoring systems allow standardized academic reporting of tumor characteristics and predict PN outcomes (complications, remnant function, possibly histology). Anatomy-based novel surgical approaches may reduce ischemic time during PN; these include early unclamping, segmental clamping, tumor-specific clamping (zero ischemia), and unclamped PN. Cancer cure after PN relies on complete resection, which can be achieved by thin margins. Post-PN renal function is impacted by kidney quality, remnant quantity, and ischemia type and duration.

Conclusions—Surgical renal anatomy underpins imaging, nephrometry scoring systems, and vascular control techniques that reduce global renal ischemia and may impact post-PN function. A contemporary ideal PN excises the tumor with a thin negative margin, delicately secures the tumor bed to maximize vascularized remnant parenchyma, and minimizes global ischemia to the renal remnant with minimal complications.

Patient summary—In this report we review renal surgical anatomy. Renal mass imaging allows detailed delineation of the anatomy and vasculature and permits nephrometry scoring, and thus precise, patient-specific surgical planning. Novel off-clamp techniques have been developed that may lead to improved outcomes.

1. Introduction

The incidence of renal tumors has been increasing over the past several decades [1]. The majority of these tumors are diagnosed at clinical stage T1 [2] and are amenable to partial nephrectomy (PN), which is the accepted surgical treatment. More recently, minimally invasive PN has become a viable alternative to open PN (OPN) and is routinely performed at many centers worldwide [3]. Much effort has been made to integrate the anatomy of the renal mass and its vasculature into current concepts [4,5]. A detailed understanding of surgical anatomy is necessary to optimize preoperative planning and operative technique, thus providing a basis for maximizing oncologic and functional outcomes. The purpose of this article is to provide a contemporary overview of renal surgical anatomy and anatomy-based issues for PN surgery, such as imaging, nephrometry scoring systems, novel vascular control techniques that reduce global renal ischemia, and factors impacting post-PN function and oncologic outcomes.

2. Evidence acquisition

The Medline, Embase, and Web of Science databases were searched without time limit on August 1, 2014 using the terms “partial nephrectomy” OR “nephron-sparing surgery” in conjunction with “anatomy” (MeSH), ”ischemia”, “renal function”, “margin”, “adrenalectomy”, “lymphadenectomy”, OR“complications”. Both free -text protocols and medical subject headings (MeSH) were used in Medline, while free-text protocols were run in Embase and Web of Science. Autoalerts in Medline were also run, and reference lists of original articles, review articles, and book chapters were searched for further eligible articles. The search was limited to the English literature. Articles that did not address the topics were excluded, and the full text of the remaining articles was reviewed. A list of articles that were judged to be highly relevant by the junior and senior authors was circulated among the coauthors, and a final consensus was reached on the structure of this review and the articles included. In addition, during writing of the manuscript, pertinent contemporary articles were identified in an attempt to include the most recent data.

3. Evidence synthesis

3.1. Surgical anatomy of the kidney

The right kidney is located approximately 1–2 cm lower than the left kidney because of the location of liver. The diaphragm covers the upper third of the kidneys posteriorly, where there is also a close relationship to the pleura that extends to the level of the 12th rib. Anteriorly, the right kidney is bordered by the liver and the right colonic flexure. The descending part of the duodenum with the head of pancreas overlies the right renal hilum. The left kidney is bordered anteriorly by the left colonic flexure. The left renal hilum is in close anatomic relation to the body of the pancreas and the splenic vessels. The upper pole of the kidneys abuts the adrenal gland, which may cap the kidney or cradle the renal hilum, especially on the left. The posterior aspect of the kidney lies on the psoas muscle [6]. Therefore, it is important to realize that the upper pole lies medially and in a posterior plane relative to the lower pole. Computed tomography (CT) slices are commonly recorded at a right angle to the body, but because of the aforementioned angulation of the kidney, this is

not necessarily at right angles to the kidney. Thus, an upper-pole tumor may occasionally appear on CT scan images as a mid-renal tumor. Therefore, for accurate imaging, appropriate adjustment of cross-sectional CT slices is required, taking into account the angulation of the kidney.

Gerota's fascia encloses the kidney, adrenal gland, and perinephric fat. Its layers are fused superiorly, laterally, and medially, but not inferiorly. Classically, the structures of the renal hilum are, from anterior to posterior, a single renal vein, a single renal artery, and the renal pelvis. The hilar region is rotated somewhat anteriorly because of the psoas muscle [7,8].

3.1.1. Arterial system—In approximately 75% of cases, a single renal artery arises bilaterally from the lateral portion of the abdominal aorta immediately caudal to the origin of the superior mesenteric artery. Duplication of renal arteries is more common on the right side (Fig. 1); duplicate arteries are often similar in caliber, with the exception of accessory renal arteries, which occur in approximately 25% of patients. These accessory arteries usually arise from the aorta and commonly subtend the poles. An accessory artery is defined as any supernumerary artery that reaches the kidney. If the artery does not enter the kidney at the hilum (eg, enters the parenchyma at a pole), it is called aberrant. An accessory artery may therefore be aberrant (but is not always so). Accessory arteries to the upper pole are typically smaller in diameter than those to the lower pole. The right renal artery passes behind the inferior vena cava (IVC) and is typically posterior and superior to the left and right renal veins. In approximately 30% of cases, the renal artery is located anterior to the renal vein. The left renal artery is higher than the right [6,9].

In relation to the renal pelvis, the renal artery forms an anterior division, which carries 75% of the blood supply, and a posterior division, which carries 25% of the blood supply. These divisions are most often formed outside the renal hilum [9]. Extra- and intraparenchymal arterial sections can be distinguished (Fig. 2). Along the lateral border of the kidney, between the arterial divisions, lies the avascular plane (Brödel's line), which is located in the axis of the posterior. This avascular plane is not in the exact mid-lateral portion of the kidney, but is located slightly posteriorly. Brödel's line can be used for avascular access for anatrophic nephrolithotomy and for endophytic tumors.

From the arterial divisions, five segmental arteries originate, including an apical, upper, middle, lower, and posterior segmental artery (Fig. 3) [10]. The first four segmental arteries arise from the anterior division, and the last segmental branch arises from the posterior division. Segmental arteries are end arteries and do not provide adequate collateral circulation. Ligation of a segmental artery causes irreversible ischemia to that segment of the kidney and subsequent segmental renal infarction. This involves limited parenchymal areas in the case of an anterior segmental artery, but occlusion of the posterior segmental artery can result in infarction of almost the entire posterior aspect of the kidney. A high percentage of patients shows anatomic variants of Graves' initial classification [10], especially for the lower segmental artery, which may arise from the main renal artery, its anterior division, the upper segmental artery, or as an accessory artery from the abdominal aorta [6]. Segmental arteries give rise to interlobar arteries at the level of the fornix, and these continue in the interlobar septae between the pyramids. At the corticomedullary junction, each interlobar

artery branches into five to seven arcuate arteries, which in turn branch into interlobular arteries. Interlobular arteries supply the afferent glomerular arteries.

3.1.2. Venous system—The peritubular capillary venous plexus drains through venae rectae into the arcuate veins. Similar to the arterial system, arcuate veins drain into the interlobular vein, which forms several trunks (two in ~50%, three in ~30% of cases) that unite as the renal vein anterior to the renal pelvis. Anastomotic longitudinal venous arcades are present within the kidney. These veins are not terminal, so the major branches can be surgically ligated without the risk of venous obstruction. A retropelvic vein, which drains some of the posterior part of the kidney, is present in two-thirds of cases [6].

The right renal vein drains directly into the IVC. There are usually no tributaries; rarely, the right gonadal vein may drain into the right renal vein. Duplication is found in 15–20% of cases. In contrast to the arterial system, isolated accessory polar veins are a rarity. The left renal vein is approximately two to three times longer than the right renal vein, enters the IVC anterior to the aorta, and is infrequently duplicated. In such instances, a retroaortic left renal vein may be present, and is often circumaortic to reflect branches anterior and posterior to the aorta. Left renal vein tributaries include the gonadal vein, adrenal vein, inferior phrenic veins, the first or second lumbar veins, and paravertebral veins in one-third of cases. The rich anastomotic structure makes it possible to ligate the left renal vein medially via IVC occlusion in the case of an IVC thrombus for a right-sided renal cell carcinoma (RCC) or during surgery for an abdominal aortic aneurysm [6].

3.1.3. Radially oriented intrarenal architecture—The intrarenal anatomy is radially oriented. This fact can be taken advantage of when performing PN. The intrarenal arteries, veins, and calyces fan out radially from the renal hilar sinus towards the lateral convex border of the kidney. Thus, a radial nephrotomy incision during unclamped PN is less likely to transect a major intrarenal vessel, and may therefore result in less bleeding than for a nonradial incision. In addition, the renal parenchyma and pyramids are similarly radially oriented. Therefore, during enucleative PN, an appropriate enucleative plane can typically be identified and then developed bluntly in close vicinity to the tumor capsule. This radially oriented parenchyma lends itself to atraumatic blunt separation of the renal parenchyma rather than sharp cutting.

3.1.4. Kidney tumor-parenchyma interface—During enucleative PN, excision is performed immediately adjacent to the tumor edge. To better inform the anatomic and oncologic propriety of enucleative PN, histologic examination of the tumor-parenchyma interface was performed on 124 nephrectomy specimens [11]. Some 82% of malignant tumors had an intrarenal pseudocapsule (PC) with a median thickness of 0.6 mm. PC invasion was noted in 45% of the cancers overall; however, no patient had a positive surgical margin. Inflammation, nephrosclerosis, glomerulosclerosis, and arteriosclerosis decreased with increasing distance from the tumor edge. The mean arteriolar diameter decreased with tumor proximity. The authors concluded that PN excision adjacent to the tumor edge appears to be histologically safe. Since the peritumoral parenchyma is histologically altered/compressed with fewer/smaller arterioles, this appears to be a surgically favorable plane for enucleative PN. Since 18% of cancers lacked an intrarenal PC and 25% of pT1a cancers had

intrarenal PC invasion, extreme care is necessary to avoid positive margins during enucleative PN [11].

3.2. Partial nephrectomy planning

3.2.1. Imaging of renal tumors and the vascular system—An understanding of the renal anatomy and vasculature is necessary for preoperative surgical planning. Imaging must delineate the relationship of the mass to adjacent normal structures and demonstrate the vascularity of the tumor.

Bi- or triphasic contrast-enhanced CT of the abdomen is the reference standard for primary imaging and staging. According to the American College of Radiology Practice Guidelines, the CT slice thickness should be 5 mm or less [12]. Masses are classified as solid or cystic, with subclassification of the latter according to Israel and Bosniak [13]. The multidetector CT (MDCT) protocol includes a non-contrast phase, a corticomedullary phase (after 40 s), a nephrographic phase (90 s), and a urographic phase (7 min). Enhancement of >15–20 Hounsfield units (HU) is considered the most important indicator of malignancy and is best assessed in the nephrographic phase. The corticomedullary phase is used to assess the arterial system (number of renal arteries, feeding mass arteries) and the urographic phase to assess proximity to and involvement of the renal collecting system [14]. Three-dimensional CT reconstruction depicts the vascular and renal mass anatomy in a format familiar to surgeons and serves to guide PN surgery, especially in complex cases [15,16].

Although CT remains the standard for primary imaging of renal masses, it has limited ability to characterize masses of <1 cm in diameter and carries radiation exposure [14]. Dual-energy CT (DECT) has the potential to lower radiation exposure by approximately 50%. DECT involves simultaneous acquisition of CT data at two different energy settings. Different materials show distinct attenuation levels at a given energy setting, allowing for material decomposition [14]. If iodine is removed from the post-contrast image, a virtual non-contrast image is acquired. For characterization of renal masses, DECT has similar accuracy to conventional two-phase CT examinations with a true non-contrast phase [17]. Although initial data are convincing, DECT technology is not yet broadly available and further data are required.

Macroscopic fat (less than −20 HU) can generally be observed on CT scans of angiomyolipomas, so these can be differentiated from other renal tumors. It is important to note that the fat content may be difficult to diagnose in small angiomyolipomas because of the volume averaging effect and a proportion of angiomyolipomas are fat-poor. Oncocytomas are typically hypervascular and homogeneous and may have a characteristic central stellate scar; however, CT features cannot reliably distinguish an oncocytoma from other renal tumors [18]. Papillary and chromophobe RCCs generally exhibit lower and more heterogeneous enhancement than clear-cell RCC [19,20], but subtypes are more difficult to differentiate in small masses. In terms of tumor size, studies indicate that CT imaging overestimates pathologic size by a small amount. The size tends to be overestimated small tumors and underestimated for larger tumors [21].

Magnetic resonance imaging (MRI) is an alternative imaging procedure and is commonly used as a problem-solving tool in patients with indeterminate CT scans (eg, for complex cystic lesions, very small masses, enhancement of 10–20 HU) or contrast medium allergies [22]. Compared to CT, MRI may be better for detecting perirenal fat invasion and evaluating the cranial and caudal extent of a venous thrombus in the IVC, as well as delineating benign thrombus from tumor thrombus [14]. Functional and advanced imaging techniques such as diffusion-weighted and perfusion-weighted imaging are expected to expand the role of MRI in the future [23].

Renal ultrasound can distinguish cystic from solid masses, may assist in identifying angiomyolipoma, and can show vascularity with the additional use of ultrasound contrast agents, including microbubbles. Because it is both less accurate than CT or MRI and user-dependent, ultrasound has a limited role in preoperative surgical planning [24]. Furthermore, assessment of the IVC and retroperitoneal nodes is often limited by bowel gas and body habitus [14]. Intraoperative ultrasound is most commonly used for intraoperative localization, to screen for additional small lesions, to confirm ischemia following clamping, to assist in obtaining negative resection margins during PN, to enable renal mass biopsy, and to guide probe placement for thermal ablation. Intraoperative ultrasound reveals additional findings not observed on preoperative imaging in approximately 10% of patients undergoing PN. This alters surgical management in the majority of cases [25].

3.2.2. Nephrometry scoring systems—Anatomy-based nephrometry scores are assigned from preoperative imaging and delineate renal mass characteristics and the relationship to adjacent structures [26]. Use of standardized objective and reproducible measures minimizes interobserver variability. Nephrometry scores can inform the surgeon regarding technical difficulty during PN for a given mass, and have been correlated with ischemia time, operation time, blood loss, complications, and the likelihood of conversion from PN to radical nephrectomy (RN). Nephrometry scoring systems can assist in clinical decision-making on RN versus PN or open versus minimally invasive PN [27].

3.2.2.1. RENAL score: The RENAL nephrometry score consists of five anatomic radiologic properties: (R)adius/maximal tumor diameter, (E)xophytic/endophytic properties, (N)earness to the collecting system or sinus, (A)nterior(a)/posterior(p)/not anterior or posterior (x) descriptor, and (L)ocation relative to the polar line. The polar lines are defined by the planes in which the medial lip of parenchyma is first seen. The suffix hilar (h) is added for tumors that abut the main renal artery or vein (Table 1) [28].

For each variable except A, one to three points are assigned, which yield a total of 3 points for the least complex and 12 points for the most complex mass. The score is read as each individual variable (eg, 1 + 2 + 2 + A + 3) summed to a score and followed by the polar location (eg, 8A). Masses are classified as low complexity (RENAL score 4–6), moderate complexity (score 7–9), or high complexity (score 10–12). An online tool has been developed to facilitate calculation at the point of care (www.nephrometry.com).

3.2.2.2. PADUA classification: The Preoperative Aspects and Dimensions Used for an Anatomical (PADUA) classification consists of six scoring parameters and an anterior/

posterior descriptor. The variables include polar location, exophytic/endophytic rate, renal rim, involvement of the renal sinus, involvement of the urinary collecting system, and maximal tumor size (Table 1) [29]. The polar lines are defined as the upper and lower margins of the renal sinus fat. The classification is given as a single sum of these parameters, with a minimum score of 6 and a maximum of 14. Stratification may be according to low complexity (score 6–7), moderate complexity (score 8–9), or high complexity (score 10–14) given the fact that this correlates with the risk of overall complications [29].

3.2.2.3. Centrality index: The centrality index (CI) differs substantially from the RENAL score and PADUA classification. CI is a continuous index based on tumor size and distance from the periphery of the tumor to the center of the kidney [30], which are thought to be the most important factors that determine resection difficulty. CI is defined as the ratio of c to the tumor radius r (diameter/2). The variable c equalizes the distance from the tumor center to the kidney center and may be calculated according to the Pythagorean theorem on axial images. For a tumor in the kidney center, CI = 0. CI increases with increasing distance of the tumor periphery from the kidney center, and surgical resection becomes easier. An online spreadsheet facilitating CI calculations is available (http://my.clevelandclinic.org/Documents/Urology/CentralityIndex2.xls).

3.2.2.4. Contact surface area: The larger the surface area of contact between a tumor and its surrounding uninvolved renal parenchyma, the greater are the amount of kidney tissue excised and the extent of renorrhaphy required during PN surgery. Contact surface area (CSA) is a descriptive, CT-based radiologic data point that may better reflect tumor complexity by numerically combining two important aspects, tumor size and percentage endophytic component, into a single radiologically measurable parameter. Using three-dimensional rendering software, the tumor circumference and its intraparenchymal component are manually rendered. Image-processing software then automatically calculates the volume of the tumor and its intraparenchymal component. The total surface area (TSA) of the tumor is calculated using the formula $4\pi r^2$ (r = tumor radius). CSA is derived by multiplying TSA by the percentage intraparenchymal component. For 162 tumors, CSA >20 cm^2 predicted adverse tumor characteristics (greater tumor size, volume, complexity) and perioperative outcomes (more parenchymal volume loss, blood loss, complications) compared to CSA <20 cm^2. Interobserver concordance of CSA was excellent [31].

3.2.2.5. Summary of studies on nephrometry scoring systems: As shown in Table 1, there are few differences in the RENAL and PADUA scores for a given renal mass. The scores are highly correlated (correlation coefficient 0.8) [32]. Both systems assign almost the same points for maximal tumor size. The only difference is for a tumor with a maximal size of7.0 cm, which would be scored as 2 according to RENAL and 3 according to PADUA. In the PADUA classification, the renal sinus and collecting system are scored separately on a scale of 1–2, compared to a single three-tiered variable in the RENAL system. Because of differing definitions of polar lines, the polar location may be assigned differently (Table 1). The two systems show good agreement, with correlation of 0.7–0.9 [33–37]. Although CI contains only two variables, the coefficients for correlation with the RENAL and PADUA scores are remarkable (0.4–0.6) [32]. While CSA correlates well with the RENAL, PADUA,

and CI systems, initial data suggest that CSA may be more accurate in predicting certain perioperative events [31].

There have been numerous studies on nephrometry scoring systems. Detailed descriptions are beyond the scope of this article. Although there are conflicting data, the majority of studies indicate that the systems are similarly effective in predicting the risk of overall complications, estimated blood loss, length of hospital stay, and ischemia time (Table 2). Several reports have correlated nephrometry scores with postoperative renal function [32,34,38]. Nephrometry parameters have been associated with pathological factors. Based on parameters of the RENAL score, nomograms predicting malignancy and high grade were developed [39]. For both nomograms, maximal tumor size (variable R) was the most important nephrometric variable. The area under the curve was 73% and 76% for malignancy and high grade, respectively. External validation revealed an area under the curve of 73% for prediction of high-grade disease [40]. Likewise, recent studies showed that higher tumor complexity according to the RENAL score is associated with high-grade disease and clear-cell subtype [41,42].

3.3. Optimizing PN outcomes

3.3.1. Optimizing functional outcomes of PN—Multiple factors impact renal functional outcomes after PN, including preoperative renal function, comorbidity, age, gender, tumor size, percentage volume preservation, and ischemia time [43]. Overall, the two surgically relevant principles for optimizing post-PN functional outcomes are to maximize volume preservation and minimize ischemia. The volume of parenchyma preserved is potentially more important than short-duration ischemia time, especially in healthy patients with normal function at baseline [44,45].

3.3.1.1. Maximizing volume preservation: As discussed in Section 3.3.2, the margin width should be minimized while ensuring a negative margin [3]. Generalized through-and-through oversuturing of the PN bed may be minimized to reduce ischemic damage to adjacent healthy remnant parenchyma, although this concept has not been proven. Suturing of the PN bed may even be avoided in selected cases [46]. There are several methods available to evaluate the amount of renal parenchyma preserved. Subjective surgeon assessment of preserved volume may provide an estimate comparable to more time-consuming imaging techniques, including cylindrical measurements obtained from preoperative and postoperative CTs [47] or three-dimensional imaging [48].

3.3.1.2. Minimizing ischemia: During PN, the main artery is routinely clamped to minimize blood loss and create a relatively bloodless field for tumor excision and renal reconstruction. However, arterial clamping leads to ischemic damage of the renal parenchyma. Several models have been proposed to study the effects of ischemia on renal function, such as the solitary kidney [49]. There is no agreement on the precise cutoff time for the onset of durable renal damage during warm ischemia [50–53]. Ischemia time should be interpreted as a continuum whereby increasingly prolonged ischemia times are more likely to cause acute kidney dysfunction [49,53]. A recent report indicated that patients with baseline medical chronic kidney disease had worse long-term outcomes after PN than those with surgically

induced chronic kidney disease [54]. Elderly patients with comorbidities (diabetes, hypertension) and pre-existing renal dysfunction at baseline are likely to have compromised kidneys with glomerulonephro-arteriosclerosis due to medical renal disease. These compromised kidneys are proboably more acutely susceptible to even shorter ischemic insults compared to healthy younger individuals with normal kidney function at baseline. Thus, recent efforts continue to be directed towards minimizing ischemic injury.

The classical strategy to limit ischemic damage is the induction of hypothermia (cold ischemia). Surface cooling with ice slush decreases renal energy expenditure and partly ameliorates the adverse impact of warm ischemia and reperfusion injury [55,56]. A nonrandomized comparative study revealed a similar decrease in glomerular filtration rate (GFR) at 3 mo after warm or cold ischemia, although the median cold ischemia time was substantially longer (45 vs 22 min) [44]. Many surgeons prefer to use mannitol and/or furosemide during PN, which may optimize reperfusion and increase diuresis [57]. However, several recent studies do not support the use of mannitol during PN [58], even in solitary kidneys [59]. Cooling with ice slush is the classical strategy for cold ischemia during OPN [56], but has also been applied in minimally invasive approaches [60,61].

As routine induction of cold ischemia is still technically arduous, several anatomic methods have been proposed to reduce the extent and duration of warm ischemia. From a practical perspective, the most technically relevant, surgically modifiable factor that impacts remnant function after PN is the duration or extent of ischemia. Global renal ischemia time is significantly reduced by early unclamping of the main renal artery, which is performed immediately after placement of the initial central running suture [62]. Compared to standard clamping in PN, warm ischemia times are reduced by >50% (mean 31.1 vs 13.9 min), while estimated blood loss and bleeding complications are similar [62]. In another study, mean warm ischemia time was reduced from 28 to 18.5 min [63].

Clamping of the main artery results in the greatest ischemic insult, which can be reduced by selective clamping of only the pertinent segmental artery(ies) [64]. The selective clamping technique is primarily used in minimally invasive PN, but Nohara et al [65] were also able to apply selective arterial clamping during OPN; however, a segmental renal artery could be isolated in only half of cases. Selective arterial clamping may not be feasible in certain instances such as dense or adherent perirenal fat or short segmental arteries [64].

Clamping of distally located, tumor-specific, higher-order segmental renal artery branches in minimally invasive PN has been described [66]. Zero-ischemia PN refers to superselective clamping of tumor-specific tertiary or quaternary artery branches. In another series, this was performed successfully in 84% of patients undergoing laparascopic PN (LPN). Compared to clamping of the main renal artery, blood loss was greater (238 vs 154 ml), but patients who had segmental renal artery clamping had significantly better renal function at 3–6 mo [67,68]. Since arterial blood flow to the remnant kidney is not interrupted, global renal ischemia is eliminated [69,70]. Tumor-specific arterial branches are microdissected and superselectively clamped with micro-bulldog clips. Selective arterial control is confirmed intraoperatively by color Doppler sonography [69,70], hyperspectral imaging [71,72], or robotic vascular fluorescence imaging [73]. In an initial study of 15 patients, there was no

change in estimated GFR (eGFR) [66]. Additional studies showed that the ipsilateral renal function decreased by approximately 10% [74]. The rate of major and minor complications was 0% and 18%, respectively [70], which is comparable to other techniques. Oncologic control with negative surgical margins was achieved in all patients [66,70,74]. Zero-ischemia minimally invasive PN appears best suited for medially located or hilar tumors [66].

If the tumor has favorable anatomic features (small size, exophytic lesion, low nephrometry scores), PN may be performed without any vascular clamping whatsoever. Tumor excision and renal reconstruction are performed unclamped. This approach can reduce the incidence of acute renal failure in patients with a solitary kidney [75]. There have been several studies on this approach; the majority of tumors were removed by OPN [76,77]. In one report on 101 patients, LPN was performed without clamping and suturing; however, more than 95% of the tumors had low nephrometry scores. Split-renal functional outcomes at 1 yr were unchanged from preoperative data [46]. Studies revealed an increase in estimated blood loss for this approach without an increase in transfusion rates [78], whereas others seemed to show increased transfusion rates [77]. Clampless minimally invasive PN may be aided by prior superselective embolization of tumor-specific arteries [79,80], prior radiofrequency ablation [81], and parenchymal clamping [82] in select cases. In minimally invasive PN for selected tumors, a bolster can be omitted [83]. The defect can be closed with an intraparenchymal running suture and thrombin sealant. This obviates the need for parenchymal renorrhaphy suturing and shortens ischemia time.

The issue of improving renal functional outcomes by decreasing warm ischemia time is not yet settled. Several studies indicate that the amount of renal parenchyma preserved, but not the type or duration of ischemia, is significant in multivariate analysis [44,45]. Conversely, a recent report indicated that decreasing warm ischemia times resulted in superior renal functional outcomes after correcting for volume loss. In serial cohorts with similar preserved parenchyma volumes and ischemia times of 36, 32, 15, and 0 min, actual eGFR outcomes exceeded volume-predicted eGFR outcomes only in the zero-ischemia cohort (−9.5%, −11%, − 0.9%, and +4.2%, respectively; $p < 0.001$) [84]. Further prospective studies are necessary to clarify this issue.

3.3.2. Optimizing oncologic outcomes of PN—Positive surgical margins occur in approximately 3% of cases after PN [85]. Historically, a 1-cm rim of healthy parenchyma was recommended to allow optimal local tumor control [86]. The width of the negative margin does not affect local tumor control [87]. In patients with a positive margin, only 7% of reoperated renal remnants had viable cancer cells [88]. Thus, the width of the negative margin can be kept to a thin, uniform rim of normal parenchyma. Intraoperative frozen section analysis is not definitive and has limited clinical significance [89], so can be omitted in the setting of complete gross resection.

Enucleative PN (tumor enucleation) along the natural plane between the tumor PC and renal parenchyma is an alternative approach for preserving the maximal amount of renal parenchyma [90]. There have been some doubts regarding local tumor control, but data from nonrandomized observational studies indicate similar oncologic outcomes compared to RN in appropriately selected patients [91]. However, it is noteworthy that some tumors do not

have a PC, and thus may not qualify for enucleation [92]. Even if the tumor penetrates through the pseudocapsule in healthy parenchyma, enucleation with a negative margin status can be achieved [93]. Enucleation may be accompanied by diathermy or laser ablation of the tumor bed.

3.3.3. Minimizing PN complications—The two main procedure-related renal complications of PN are hemorrhage and urinary leakage. Risk factors for complications can be classified as anatomic, surgical, or patient-related. Anatomic risk factors are summarized in the nephrometry scoring systems, which correlate with the overall risk for complications [94–96]. Anatomic and patient-related factors cannot be modified, but can guide the surgical approach.

The incidence of complications is well documented in the prospective EORTC 30904 trial. Perioperative blood loss was <0.5 l in 17.1%, 0.5–1.0 l in 9.7%, and >1.0 l in 3.1% of cases [97]. In addition to coagulopathy and intraoperative vascular injuries as patient-related and surgical risk factors, proximity to the collecting system [95] and tumor size [98] are established anatomic risk factors for perioperative hemorrhage (intra- and postoperative). In a multicenter study of 730 elective OPNs, the rate of blood transfusions for tumors ≤4 cm and >4 cm was 6.3% and 14.8%, respectively [98]. ASA score ≥3 (OR 2.9) and smoking (OR 3.5) were identified as additional patient-related risk factors for blood transfusion following LPN [99]. LPN appears to be associated with lower intraoperative blood loss, but a higher rate of postoperative hemorrhage [100]. Most patients with postoperative hemorrhage can be managed conservatively; some require embolization and a minority need reoperation [100,101]. Precise operative technique and intraoperative hemostasis are cornerstones in preventing postoperative hemorrhage. Hemostatic agents and tissue sealants are frequently used as an adjunct to conventional hemostasis by coagulation and suturing, especially after LPN [102]. They improve hemostasis [103,104], but there is a lack of data from randomized studies.

Urinary leakage occurs in approximately 4–5% of cases [97,105]. Proximity to the collecting system, and thus a higher nephrometry score, is associated with postoperative urinary leakage [106]. Tumor size is another main risk factor, with the incidence increasing twofold for tumors >2.5 cm [105]. Urinary leakage can be managed conservatively with a ureteral stent or percutaneous drainage [101]. Preoperative insertion of a ureteral catheter allows retrograde filling to identify opening of the urinary collecting system, although this did not decrease the rate of postoperative urine leaks [107]. A renal pelvic anatomy score (RPS) has been developed [108] and validated [96,109]. The RPS is defined as the percentage of renal pelvis inside the renal parenchyma volume, categorized as intraparenchymal (>50%) or extraparenchymal (<50%) renal pelvis. Intraparenchymal renal pelvic anatomy is associated with a markedly higher risk of urinary leakage, which in turn may guide perioperative management [108,109].

Reporting of composite outcomes of PN using a trifecta system (negative margins, functional preservation, no urologic complications) has recently been proposed and is likely to increase in relevance [84]. Importantly, the definition of trifecta outcomes is not standardized and several different criteria have been used [84,110,111].

4. Conclusions

Over the past decade, PN surgery has been evolving towards an ideal PN. Renal mass imaging allows detailed delineation of the anatomy and vasculature and permits nephrometry scoring, and thus precise, patient-specific surgical planning. Novel techniques have been developed that minimize global renal ischemia during PN. A contemporary ideal PN excises the tumor with a thin negative margin, precisely secures the tumor bed, and reduces global ischemia to the renal remnant with minimal complications.

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Take Home Message

Surgical renal anatomy underpins imaging, nephrometry scoring systems, and novel vascular control techniques that reduce global renal ischemia and may impact postoperative renal function. A contemporary ideal partial nephrectomy excises the tumor with a thin negative margin, delicately secures the tumor bed to maximize vascularized remnant parenchyma, and reduces global ischemia to the renal remnant with minimal complications.

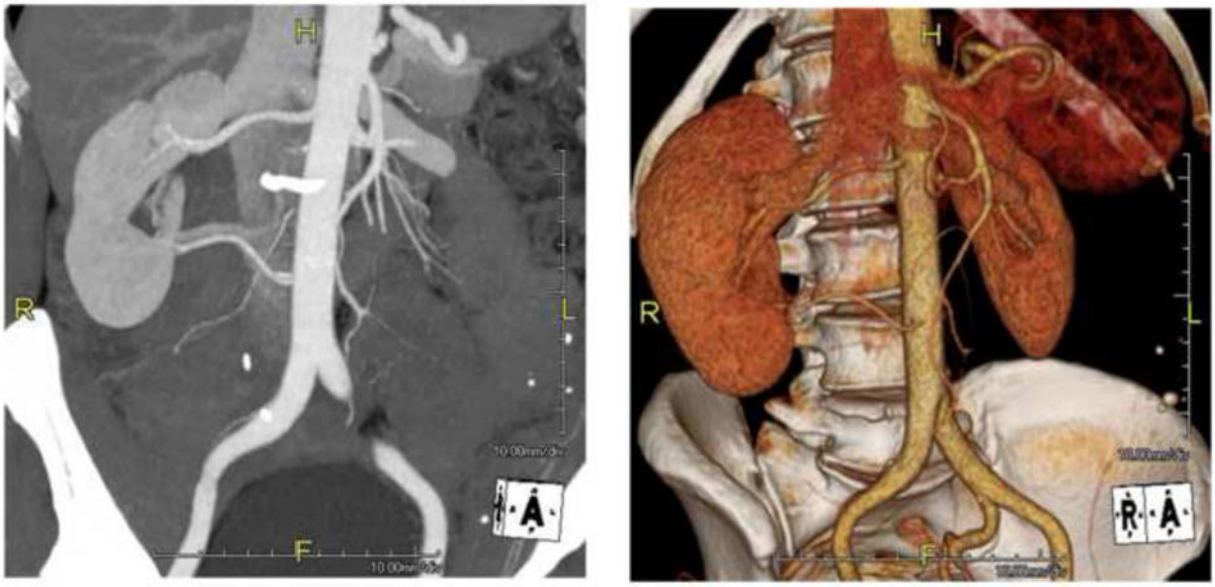

Fig. 1.

Computed tomography scan showing two right renal arteries. Courtesy of V. Ficarra, University of Udine, and V. Macchi, University of Padua.

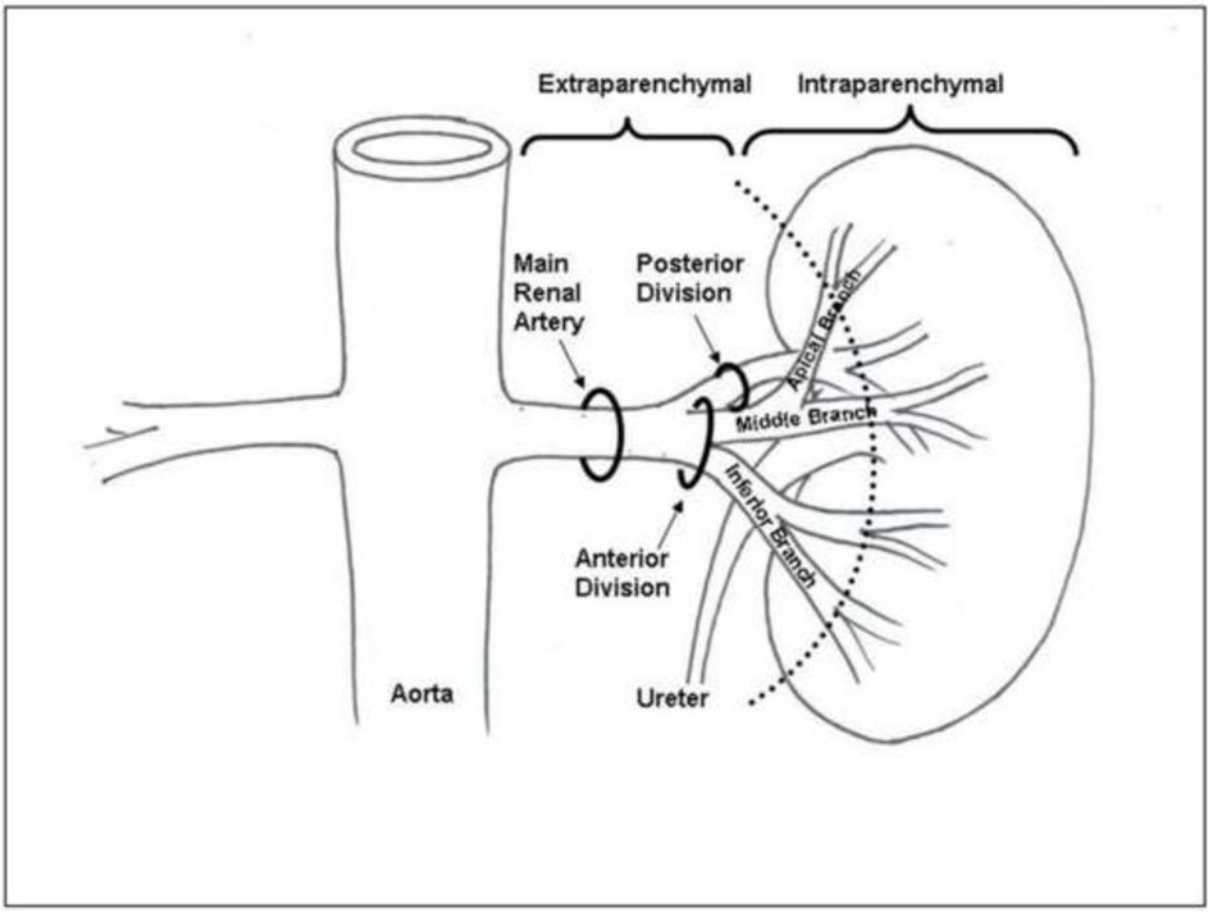

Fig. 2.

Anatomy of the left renal artery. Extra- and intraparenchymal arterial sections are distinguished. Courtesy of V. Ficarra, University of Udine, and V. Macchi, University of Padua.

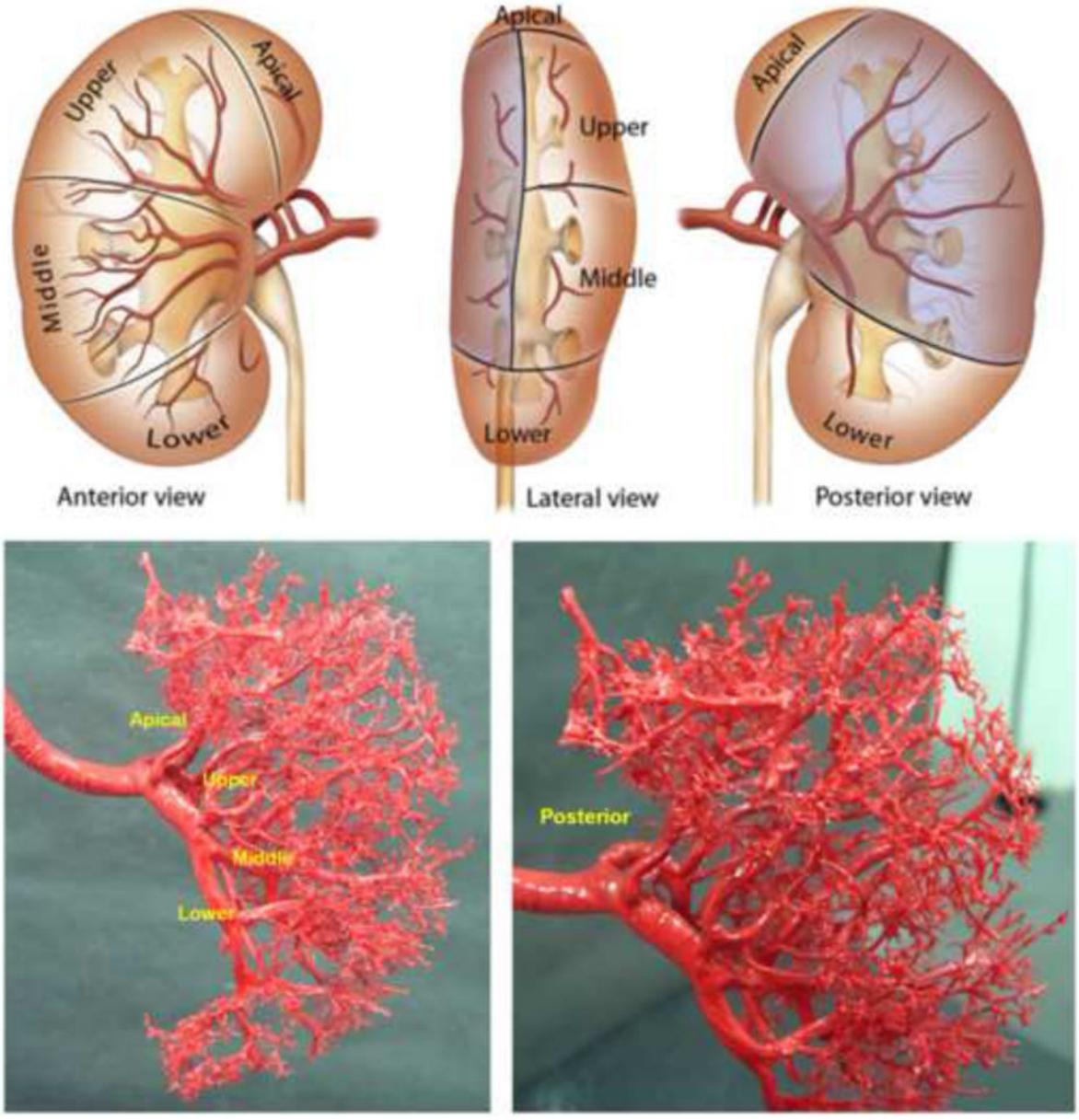

Fig. 3.

Graves' anatomic classification of segmental renal arteries. In addition to the classical variant, a high percentage of patients show anatomic variations. Courtesy of V. Ficarra, University of Udine, and V. Macchi, University of Padua.

Table 1

Overview of the parameters of the RENAL and PADUA scoring systems

Variable	RENAL	PADUA
Maximal tumor diameter	1 point: ≤4 cm	1 point: ≤4 cm
	2 points: >4 – <7 cm	2 points: 4–7 cm
	3 points: ≥7 cm	3 points: >7 cm
Exophytic/endophytic rate	1 point: ≥50%	1 point: ≥50%
	2 points: <50%	2 points: <50%
	3 points: endophytic	3 points: endophytic
Collecting system	Or renal sinus	1 point: not involved
	1 point: proximity >7 mm	2 points: dislocated/infiltrated
	2 points: proximity 4–7 mm	
	3 points: proximity ≤4 mm	
Polar location	1 point: entirely above or below the polar lines	1 point: superior/inferior [b]
	2 points: crosses the polar line	2 points: middle
	3 points: >50% crosses the polar line or crosses the axial renal midline or entirely between the polar lines	
Renal rim	–	1 point: lateral
		2 point: medial
Renal sinus	Included in collecting system	1 point: not involved
		2 points: involved
Anterior/posterior	No points	No points

[a] Polar lines are defined as the plane of the kidney above or below which the medial lip of parenchyma is interrupted by the renal sinus fat, vessels, or the collecting system on axial imaging.

[b] Polar lines are defined according to the renal sinus.

Table 2

Selected validation studies for the RENAL score, PADUA classification, and C index

Reference	*n*	Complications	Ischemia time	Blood loss	LOS
RENAL score					
Hayn et al [112]	141 LPN	NS	+	+	+
Simhan et al [96]	216 OPN, 174 RPN	Major (CCS 3–5)	+	+	+
Hew et al [33]	134 PN	+	+	NA	NA
Kruck et al [113]	81 LPN	NS	NS	+	+
Lavallée et al [35]	78 OPN	NA	+	NA	NA
Bylund et al [32]	124 LPN, 25 RPN, 13 OPN	NA	+	+	NA
Png et al [36]	83 RPN	NS	+	NS	NA
Long et al [114]	159 OPN, 18 LPN	NS	NS	NS	NS
Stroup et al [106]	153 OPN, 100 LPN, 31 RPN	Urine leak, but NS overall	NA	NA	NA
Mayer et al [115]	55 RPN, 12 LPN	NA	+	NS	NA
Liu et al [95]	128 LPN, 53 RPN	+	+	NS	NS
Altunrende et al [116]	181 RPN	NA	NS	NA	NA
Mufarrij et al [117]	92 RPN	NS	Trend ($p = 0.07$)	Trend ($p = 0.07$)	NS
Bruner et al [118]	155 PN	Urine leak	NA	NA	NA
Okhunov et al [34]	101 LPN	NS	+	NS	NS
PADUA classification					
Hew et al [33]	134 PN	+	+	NA	NA
Kruck et al [113]	81 LPN	−	NS	+	+
Lavallée et al [35]	78 OPN	NA	+	NA	NA
Bylund et al [32]	124 LPN, 25 RPN, 13 OPN	NA	+	NS	NA
Okhunov et al [34]	101 LPN	NS	+	NS	NS
Ficarra et al [94]	347 RPN	+	+	+	NA
Waldert et al [119]	186 OPN, 54 LPN	+	+	NA	NA
Kong et al [120]	136 OPN, 59 LPN	+	+	NS	NA
Mottrie et al [121]	62 RPN	+	+	+	NA
Tyritzis et al [122]	74 OPN	+	NA	NA	NA
Minervini et al [123]	244 OPN	+	NA	NA	NA

Reference	*n*	Complications	Ischemia time	Blood loss	LOS
C index					
Lavallée et al [35]	78 OPN	NA	Trend ($p = 0.06$)	NA	NA
Bylund et al [32]	124 LPN, 25 RPN, 13 OPN	NA	+	NS	NA
Okhunov et al [34]	101 LPN	NS	+	NS	+

LOS = length of hospital stay; LPN = laparascopic partial nephrectomy; OPN = open partial nephrectomy; RPN = robot-assisted partial nephrectomy; + = statistically significant association; NS = not significant; NA = not assessed; CCS = Clavien-Dindo classification system.