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Robot-assisted partial nephrectomy: Is it the future of kidney surgery? A comparison of nephron-sparing techniques in partial nephrectomy

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Abstract

Technological advancements are significantly transforming various medical fields, including urology. The increasing adoption of minimally invasive surgical techniques and robotic assistance is particularly impactful. Three partial nephrectomy techniques are investigated: open partial nephrectomy, laparoscopic partial nephrectomy, and robot-assisted partial nephrectomy. Among these, robot-assisted partial nephrectomy is considered to be superior due to shorter warm ischemia time, reduced blood loss, better early renal functional preservation, and shorter hospital stays. The zero-ischemia partial nephrectomy concept aims to improve postoperative kidney function outcomes. The integration of robotic technology and advancements in artificial intelligence and surgical training systems are expected to further enhance surgical techniques. Artificial intelligence, particularly when combined with computer vision algorithms, shows potential for creating precise and automated three-dimensional models for surgical planning in complex robot-assisted partial nephrectomy procedures, potentially leading to better patient outcomes. This review identifies the current capabilities and prospective advancements in the application of robotic technology in partial nephrectomy.

Keywords: nephron-sparing surgery, robot-assisted partial nephrectomy, laparoscopic partial nephrectomy, open partial nephrectomy, zero-ischaemia partial nephrectomy

Introduction

In the modern times, rapid technological advancements significantly impact various branches of medicine. In urology, the application of modern technologies in surgery, particularly in the context of minimally invasive surgery, is crucial. The da Vinci system, developed by Intuitive, is a widely adopted robotic surgical technology, with over 10 million surgical procedures performed globally using this system. Other robotic surgical technologies, such as Aquabeam and Mako, are also being used in the field of surgery. The use of robot-assisted surgery has the potential to improve surgical outcomes, reduce complications, and enhance patient recovery [1].

In urology surgical treatment of kidney tumors has evolved from open radical nephrectomy (ORN) to nephron-sparing surgery (NSS) techniques comprising open partial nephrectomy (OPN) and minimally invasive partial nephrectomy, which includes two methods: laparoscopic partial nephrectomy (LPN) and robot-assisted partial nephrectomy (RAPN). In the past, the standard approach to treat localized renal tumors was radical nephrectomy. Partial nephrectomy was traditionally reserved for specific clinical scenarios such as a single kidney, bilateral or hereditary renal tumors, chronic kidney disease, or a high risk of significant renal disease [2]. However, in the past decade the use of partial nephrectomy (PN) for treatment of renal tumors has markedly increased [3]. Štimac et al. emphasized the necessity for a well-powered randomized prospective clinical trial to resolve the dilemma of selecting between radical nephrectomy (RN) and partial nephrectomy (PN) [3]. Currently, according to the National Comprehensive Cancer Network, the American Urological Association, and the European Association of Urology PN is recommended if anatomically possible [4-5]. Priority of partial nephrectomy is recommended for clinical T1a lesions, along with the selective use of thermal ablation, particularly for tumors ≤3.0 cm [6]. The goal of nephron-sparing surgery (NSS) is the Trifecta concept, which includes negative surgical margins, no major complications, and maximum preservation of renal function (RF) [7]. Recent studies suggest that patients undergoing partial nephrectomy for small kidney tumors achieve equivalent oncological outcomes [8], better kidney function [9], lower incidence of cardiovascular diseases [10], and overall improvement compared to those undergoing radical nephrectomy [10-11].

Due to technique improvements over the past two decades, LPN has become a widely accepted approach to performing technically demanding partial nephrectomy procedures [12-13]. LPN was first used in 1993 and over the past three decades, has become a widely used technique in the technically demanding procedure of partial nephrectomy [14]. Performing LPN in the presence of renal tumors presents technical challenges, primarily attributed to the requirement for timely tumor excision and kidney reconstruction to minimize warm ischemia time (WIT). WIT in nephrectomy refers to the duration of time during which the blood supply to the kidney is temporarily interrupted or reduced during the surgical procedure. The length of WIT has a significant impact on both short-term and long-term renal function and is also used as a measure of the surgeon's skills in tumor removal and renal reconstruction [15].

In 2004, RAPN technique emerged a more advanced approach compared to LPN. Due to 3D visualization and optical magnification provided by RAPN, more precise tumor resection with adequate surgical margins is possible [14]. Nowadays, RAPN is considered the gold standard for surgical treatment of small masses (T1a) [17-19]. Moreover, its adoption should be considered for clinical T1b and T2 renal masses, which are associated with higher complication rates due to the larger size and increased complexity of the tumors [20].

This review is an overview of current knowledge of the expanding capabilities of robotic technology in the field of partial nephrectomy.

Methodology

Herein, we compare RAPN to other techniques of partial nephrectomy (OPN and LPN) in terms of WIT, operative time, intra- and postoperative complications, estimated blood loss, conversion rate, positive surgical margins, length of stay. The analysis of research papers on PubMed, Google Scholar, Web of Science, Embase and Scopus was undertaken, using the following keywords: “robot-assisted partial nephrectomy”, “robotic partial nephrectomy”, “partial nephrectomy”, “nephron-sparing surgery”, “zero-ischemia nephrectomy”, “warm ischemia time”, “artificial intelligence in robotic surgery”. Only articles in English were considered. We selected a total of 47 scientific articles based on eligibility criteria.

Comparison of LPN and RAPN in terms of warm ischemia time, operative time, blood loss, and conversion rate

The duration of WIT stands out as a noteworthy modifiable factor with the potential to impact postoperative renal function. Additionally, critical factors such as operative time, blood loss, and conversion rate can wield a substantial influence on surgical and economic outcomes. We focused on comparing RAPN to LPN as both techniques utilize 3D-vision and are minimally invasive in terms of the invasiveness of the procedure.

In the United Kingdom, an extensive multicenter study was conducted between 2012-2015, providing information on patient outcomes in the perioperative period after RAPN performed through a transperitoneal approach. A total of 250 patients were included in the study, with a median follow-up period of 12 months. An average WIT was 16.7 ± 8 minutes, and a median estimated blood loss (EBL) was 100 ml [21]. Whereas in a study conducted by Benway et al. [22] a total of 129 cases of patients undergoing RAPN and 118 cases of patients undergoing LPN were investigated. The study results showed that patients undergoing RAPN had significantly shorter WIT (19.7 vs. 28.4 minutes, $p<0.001$), and lower blood loss (155 vs. 196 ml, $p=0.03$). Additionally, among patients with challenging renal tumors, defined as those requiring repair of the collecting system, WIT increased for both RAPN and LPN, but RAPN maintained a significantly shorter WIT than LPN (25.9 vs. 36.7 min, $p<0.001$) [22].

In their meta-analysis, Aboumarzouk et al. [23] compared two surgical methods and reported significant findings. The study included a total of 717 patients, with 313 undergoing RAPN and 404 undergoing LPN. The RAPN group exhibited a significantly shorter WIT compared to the LPN group (mean difference = -2.74 min, $p=0.0008$). However, no statistically significant differences were found between the groups regarding estimated blood loss ($p = 0.76$), operative time ($p = 0.58$), and conversion rate ($p = 0.84$).

Cacciamani et al. [24] conducted a meta-analysis involving 20,282 patients. In the comparison between RAPN and LPN, the former proved to be superior in terms of WIT (weighted mean difference = 4.21, $p<0.0001$) [24]. Wu et al. [25] found that the RAPN was associated with significantly lower estimated blood loss (EBL; 156 vs 198 ml, MD = -42; $p = 0.025$), and shorter WIT (22.8 vs 31 minutes, MD = -8.2; $p < 0.001$).

The most recently published meta-analysis by Jiang et al. [26] compiled seven previous meta-analyses. The paper aimed to assess the perioperative outcomes and compare them between RAPN and LPN for complex kidney tumors with the RENAL Nephrometry Score ≥7. In contrast to the previously cited studies, no significant differences were found in estimated blood loss (WMD: 34.49; 95% CI: -75.16–144.14; $p = 0.54$) between the groups. Moreover, RAPN showed better outcomes in terms of operative time (WMD: -22.45; 95% CI: -35.06 to -9.85; $p = 0.0005$) and conversion to radical nephrectomy (OR: 0.34; 95% CI: 0.17–0.66; $p = 0.002$). Chang et al. [27] conducted a study using propensity score matching analysis and found that RAPN resulted in significantly lower mean blood loss compared to LPN ($p = 0.025$). Interestingly, the previously mentioned study by Jiang et al. [24] showed no between-group difference in terms of EBL, which suggests that the effect might be dependent on the characteristics of the patient group. The noteworthy study is the meta-analysis by Choi et al. [28] addressing, the difference in WIT when using RAPN and LPN. Researchers conducted a meta-analysis involving 23 studies involving 2,240 patients. The RAPN group had a shorter WIT (p=0.005), significantly lower conversion rate to open surgery (p=0.02) and conversion to radical surgery (p=0.0006), a smaller change in estimated glomerular filtration rate (eGFR; p=0.03),

Comparison of RAPN and LPN in terms of renal function, intra- and post-operative complications, length of stay (LOS), and positive surgical margins

A crucial aspect in comparing both minimally invasive methods - RAPN and LPN - involves also parameters such as intra- and postoperative complications, postoperative renal function, positive surgical margins and the length of hospital stay (LOS).

Veeratterapillay et. al. [21] observed results indicating that in RAPN median LOS was 3 days. Perioperative complications occurred in 16.4% of patients. Of the total, 66% of patients maintained their preoperative chronic kidney disease category, and none of the patients needed dialysis during the study period. The 'Trifecta' outcome was observed in 68.4% of all patients. Benway et al. [22] found that patients undergoing surgery had shorter hospital stay in the RAPN group (2.4 vs. 2.7 days, p < 0.001). There were no significant differences in the frequency of complications or immediate renal function after the procedure. Conversely, the study of Abamarzouk et al. [23] demonstrated no differences in terms of postoperative hospital stay (p = 0.37). Moreover, no differences in terms of complications (p = 0.86), or positive margins (p = 0.93). Cacciamani et al. [24] found that in comparison to LPN, RAPN resulted in improvement in several outcomes, namely intraoperative complications (Odds Ration [OR] 2.05, p>0.0001), postoperative complications (OR 1.27, p=0.0003), positive margins (OR 2.01, p<0.0001), the percentage decrease in the last estimated glomerular filtration rate (weighted mean difference (WMD) -1.97, p = 0.02)]. Wu et al. [25] reported that the rate of intra-operative complications was notably lower in the RAPN group (1.3% vs 11.7%; odds ratio 0.1, 95% confidence interval 0.01-0.81; p = 0.018). The surgical approach (RAPN vs LPN) was a significant factor (odds ratio 5.457, 95% CI 2.075-14.346; p = 0.001), along with Charlson Comorbidity Index (odds ratio 0.223; 95% CI 0.062-0.811; p = 0.023), diameter-axial-polar score (odds ratio 0.488, 95% CI 0.329-0.723; p < 0.001), and preoperative chronic kidney disease (CKD) stage (odds ratio 3.189, 95% CI 1.204-8.446; p = 0.020) as independent predictors associated with achieving a favorable outcome.

Regarding early renal functional outcomes, the mean last estimated glomerular filtration rate was 95.8 and 89.4 ml/min/1.73 m² (MD = 6.4; p = 0.01), with a mean ± SD percentage change between pre- and post-surgery of -4.8 ± 17.9 and -12.2 ± 16.6 (MD = 7.4; p = 0.018) in the RAPN and LPN groups, respectively.

In the study by Jiang et al. [26] no significant differences were found in terms of hospital stay duration (WMD: -0.59; 95% CI: -1.24–0.06; p = 0.07), positive surgical margins (OR: 0.85; 95% CI: 0.65–1.11; p = 0.23), major postoperative complications (OR: 0.90; 95% CI: 0.52–1.54; p = 0.69), and transfusion rates (OR: 0.72; 95% CI: 0.48–1.08; p = 0.11) between the two analyzed operative techniques - RAPN and LPN.

RAPN showed better outcomes in terms of postoperative renal function (WMD: 3.32; 95% CI: 0.73–5.91; p = 0.01) and intraoperative complications (OR: 0.52; 95% CI: 0.28–0.97; p = 0.04). This study demonstrated that RAPN is a safe and effective alternative for treating complex kidney tumors with a RENAL nephrometry score ≥7 compared to LPN, characterized by a shorter WIT and better postoperative renal function.

In in the previously cited study [26] the authors also demonstrated that RAPN provides a better improvement in kidney function in the postoperative period and enables a shorter length of hospital stay (LOS; p = 0.004).

All of these studies conclude that RAPN can be an equal or superior choice in terms of renal function, operative complications, transfusion rates, and LOS. However, further studies are needed to confirm the safety and effectiveness of RAPN.

Kidney function after RAPN - influence of zero ischemia and selective artery clamping on kidney function

Clamping the renal hilum is a method formerly employed to manage the renal hilum. However, it unavoidably causes ischemic harm to the kidney, posing a potential threat of diminished long-term renal function [29]. In the era of open surgery, surgeons utilized hypothermia induction, known as “cold ischemia”, to decrease kidney metabolism during clamping [30]. The outcomes of multiple research studies and the consensus among experts propose that the negative impact on renal function, resulting from a brief WIT of less than 30 minutes is temporary and undergoes spontaneous reversal [31].

The utilization of renal pedicle clamping in partial nephrectomy has sparked discussions due to its possible advantages like minimized blood loss and improved visibility of the tumor margin [32]. However, it also comes with potential drawbacks such as the risk of injuring the renal pedicle, spasms in the renal arteries, heightened risk of postoperative adhesions, and injuries to neighboring organs along with the potential loss of renal function [33]. Due to these drawbacks the concept of zero ischemia partial nephrectomy was introduced. Zero ischemia refers to a surgical technique in which there is no interruption of blood flow to the organ being operated on, in this case, the kidney. Researchers have arbitrarily applied this term to describe various techniques. Such techniques include “off-clamp” approaches, which involve no clamping of the renal hilum at all, selective clamping of the renal artery and/or vein, or selective clamping of the secondary, tertiary, or quaternary branches of these blood vessels, with or without calibrated reduction of blood pressure during surgery [29]. Early approaches in the off-clamp variation incorporated a combination of renal artery branch microdissection, highly selective clamping of tertiary branches, and pharmacologically induced controlled hypotension to achieve zero ischemia in both RAPN and LPN techniques [34,35].

The glomerular filtration rate (GFR) is the volume of fluid *filtered from the renal glomerular capillaries into the Bowman’s capsule per unit of* time. The eGFR level is one of the factors used to assess postoperative kidney function. To identify prognostic indicators of eGFR after RAPN, Wiener et al. [36] measured eGFR in 122 patients before RAPN and at 6- and 12-month follow-up durations. The study demonstrated that age, body mass index (BMI) >30, perioperative estimated blood loss (EBL) >200 ml, Charlson comorbidity index >5, and WIT >22 minutes were associated with a significant decline in eGFR. However, the multivariate analysis revealed that patient’s age was a statistically significant factor correlating with a decrease in eGFR. There are studies suggesting that even brief ischemia causes harm to the kidneys. Gill et al. [37] suggest that transient ischemia can be detrimental, especially in patients with existing comorbidities, renal function disorders, or advanced age. Hence, the term "zero ischemia" emerged to describe a technique eliminating surgically induced ischemia during operative procedures in patients undergoing partial nephrectomy. Foerster et. al. [38] in their meta-analysis based on 45 studies, found that patients undergoing RAPN with zero ischemia and selective artery clamping experienced a smaller decline in the GFR of the operated kidney compared to both warm and cold ischemia.

While traditional renal pedicle clamping may harm kidney function, brief warm ischemia time appears reversible. Zero ischemia techniques aim to preserve kidney function, with studies suggesting a lesser decline in GFR compared to traditional methods.

Off clamp vs on-clamp zero ischaemia technique in partial nephrectomy

Zero ischaemia in partial nephrectomy can be achieved using off-clamp and on-clamp techniques. Kaczmarek et. al. [39] analyzed data from multiple institutions, examining prospectively collected records of 886 Robot-Assisted Partial Nephrectomies (RAPNs) performed by highly experienced surgeons across five academic institutions from 2007 to 2011. Patients who underwent off-clamp RAPN exhibited an average tumor size of 2.5 cm and a mean RENAL nephrometry score of 5.3. The preoperative eGFR level averaged 81 (SD: 29) with mean change of eGFR at first follow-up of 3%. The mean EBL was 210 ml (SD: 212), with an average operative time of 155 min (SD: 46). No complications of Clavien grade 3–5 were observed and no patient needed postoperative dialysis. The positive surgical margin rate was 3% (n = 2), and no instances of disease recurrence were reported during a mean follow-up of 21 months. In propensity score-matched analyses, patients who underwent off-clamp RAPN experienced a significantly shorter mean operative time (156 min vs. 185 min, p<0.001), higher EBL (228 ml vs. 157 ml, p=0.009), and a smaller decrease in eGFR (2% vs. 6%, p=0.008) compared to clamped controls.

In a study conducted in 2015 by Satkunasivam et. al. [40], the technical feasibility of RAPN without clamping with minimal margin was confirmed. In a retrospective analysis of patient outcomes after RAPN with anatomical zero ischemia, 179 patients were included. They were divided into three groups: the first group, consisting of 70 patients who underwent surgery with highly selective clamping; the second group, consisting of 60 patients who underwent surgery with highly selective clamping by experienced surgeons, and the third group, consisting of 49 patients who underwent completely unclamped, minimal-margin partial nephrectomy. The median percentage reduction in eGFR was similar in all three groups after 1 month of postoperative follow-up monitoring (-7.6%, 0%, and -3.0% in the first, second, and third group, respectively; p = 0.53). However, newly diagnosed CKD stage >3 occurred significantly less frequently in the third group (23%, 10%, and 2% in the first, second, and third groups, respectively; p=0.003).

In another study, a prospective analysis of changes in kidney function was conducted on 44 patients who underwent RAPN or LPN using the zero ischemia technique, both with and without vessel microdissection [41]. Researchers clamped the tumor-bearing branches of the third-order or higher renal arteries, selecting them based on 3D reconstructed CT imaging and using microsurgical aneurysm clamps for highly selective tumor devascularization. Controlled blood pressure reduction was not used, and the WIT was zero for all patients. Functional outcomes were assessed using the median level of creatinine and eGFR after surgery. No statistically significant differences were observed between the two groups.

In the study by Papalia et al. [42] the effects of LPN and RAPN on 121 patients with zero ischemia were compared using transient controlled hypotension between two groups – as those with tumors <4 cm in diameter and those with tumors >4 cm. After three months, no significant differences in functional outcomes, especially eGFR, were observed between these groups.

Antonelli et al.[43] have written an interesting paper comparing on-clamp to off-clamp RAPN. Due to a relevant rate of shift from the assigned treatment, the per-protocol analysis was considered and the data from 129 on-clamp vs 91 off-clamp RAPNs analyzed. Tumor size (off-clamp vs on-clamp, 2.2 vs 3.0 cm, $p<0.001$) and RENAL nephrometry score (5 vs. 6, $p<0.001$) significantly differed. At univariate analysis, no differences were found regarding intraoperative estimated blood loss (off- vs on-clamp, 100 vs 100 ml, p=0.7), postoperative complications rate (19% vs 26%, p=0.2), postoperative anemia (Hb decrease>2.5 g/dl 26% vs. 27%, p=0.9; transfusion rate (3.4% vs. 6.3%, p=0.5); re-intervention due to bleeding (1.1% vs. 4%, p=0.4), acute kidney injury (4% vs. 6%, p=0.8), and positive surgical margins (3.5% vs. 8.2%, p=0.1). At multivariate analysis accounting for tumor diameter and complexity, considering the on-clamp group as the reference category, a significant difference was noted in the off-clamp group exclusively for blood loss (OR 0.3, 95% CI 0.09–0.52, p = 0.008).

In 2023 Serag et. al. [44] conducted a meta-analysis of a total of 42 studies involving 9,027 patients to compare the off-clamp technique to the on-clamp technique in terms of perioperative outcomes (i.e., EBL and postoperative blood transfusion), eGFR and tumor transection time. On-clamp PN was associated with significantly higher operative time as compared to the off-clamp group [MD = 13.54 minutes; 95% CI: 3.34-23.74; $I^2 = 97.86\%$]. The on-clamp technique was also associated with significantly lower blood loss [MD = –53.87 mL; 95% CI: –90.60 to –17.14; $I^2 = 96.94\%$], significantly lower risk for postoperative blood transfusion [logOR = –0.63; 95% CI: –0.91 to –0.35; $I^2 = 20.58\%$], lower risk for major bleeding (logOR = –0.98; 95% CI: –1.79 to –0.18; $I^2 = 0.00\%$), significantly higher postoperative eGFR levels (MD = 3.08; 95% CI: 0.95: 5.20 to –17.14; $I^2 = 45.09\%$) higher tumor size (MD = 0.30; 95% CI: 0.10 to 0.49; $I^2 = 85.05\%$) significantly lower resection time (MD = –0.92; 95% CI: –1.59 to –0.25; $I^2 = 0.00\%$); higher risk for postoperative complications [logOR= 0.30; 95% CI: 0.14 to 0.47; $I^2 = 0.00\%$], significant increase in the risk of AKI (logOR = 0.63; 95% CI: 0.08 to 1.19; $I^2 = 0.00\%$), higher risk for postoperative positive surgical margin (logOR = 0.44; 95% CI: 0.14 to 0.74; $I^2 = 0.00\%$). There was no significant difference in terms of surgical conversion to open surgery, reintervention following PN, postoperative bleeding (any severity) following PN, and reconstruction time. Also, there was no significant change between the on-clamp and off-clamp methods in terms of postoperative percent change in eGFR levels, postoperative Hb, and creatinine levels.

The comparison between on-clamp and off-clamp techniques in robot-assisted partial nephrectomy (RAPN) reveals nuanced differences in perioperative outcomes and renal function. While off-clamp RAPN tends to exhibit shorter operative times and decreased blood loss, on-clamp RAPN demonstrates advantages in postoperative renal function and lower risks of postoperative complications. These findings underscore the importance of tailoring surgical approaches based on individual patient characteristics and tumor complexity.

Comparison of RAPN and OPN

Comparing RAPN to OPN holds significant value in urological practice. As minimally invasive surgical techniques continue to evolve, it becomes essential to evaluate their efficacy, safety, and overall outcomes compared to traditional open approaches. Understanding the differences between OPN and RAPN can provide valuable insights into factors such as perioperative complications, recovery times, oncological outcomes, and renal function preservation.

Cacciamani et. al. [24] compared OPN to RAPN; the latter technique proved superior in terms of blood loss (WMD 85.01, p<0.00001), transfusion (OR 1.81, p<0.001), complications (OR 1.87, p<0.00001), hospital stay (WMD 2.26, p=0.001), readmission (OR 2.58, p=0.005), the percentage decrease in the last estimated glomerular filtration rate (WMD 0.37, p=0.04), overall mortality (OR 4.45, p<0.0001), and recurrence rate (OR 5.14, p<0.00001).

Xia et al. [45] conducted a systematic review and meta-analysis of the literature concerning perioperative outcomes of RAPN and OPN. They searched databases to identify randomized controlled trials and observational comparative studies allowing a comparison of both approaches (RAPN vs OPN). In total, they analyzed 3,551 patients undergoing surgery, with RAPN comprising 1,216 and OPN comprising 2,335 cases. In comparison with OPN, RAPN demonstrated the following benefits: lower rates of postoperative complications (risk ratio [RR]=0.60, 95% CI=0.46–0.78, p=0.0002), postoperative minor complications (RR=0.73, 95% C =0.56-0.96, p=0.02), and postoperative major complications (RR=0.50, 95% CI=0.30-

0.84, p=0.01); reduced need for transfusion (RR=0.64, 95% CI=0.41-0.98, p=0.04); less blood loss ([WMD]=-98.82, 95% CI=-125.64 to -72.01, p<0.00001); and shorter hospital stay (WMD=-2.64, 95% CI=-3.27 to -2.00, p<0.00001).

Rosiello et. al [46] compared RAPN with OPN in terms of frailty in patients. In total, 2745 patients classified as frail underwent partial nephrectomy from 2008 to 2015. Among them, 1109 individuals (40.4%) received treatment through RAPN. In multivariable logistic regression models RAPN independently predicted lower risk of overall complications (OR: 0.58; CI 0.49–0.69; p<0.001), major complications (OR: 0.55; CI 0.44–0.70; p<0.001), blood transfusions (OR: 0.60; 0.45–0.80; p<0.001) and non-home-based discharge (OR: 0.51; CI 0.39–0.66; p<0.001). In multivariable Poisson regression models, which were also adjusted for all covariates, RAPN independently predicted shorter LOS (RR: 0.77, CI 0.73–0.81; p<0.001). Comparisons between OPN and RAPN consistently favor RAPN across various perioperative outcomes, including reduced blood loss, lower rates of complications, and shorter hospital stays. Studies also indicate that RAPN independently predicts lower risks of overall complications, major complications, blood transfusions, and non-home-based discharge, highlighting its potential advantages over OPN in managing kidney tumors.

Discussion

The evolution of surgical techniques in urology, particularly in the treatment of kidney tumors, has seen a significant shift towards minimally invasive approaches such as RAPN. This review highlights the growing importance of robotic technology in achieving favorable surgical outcomes, including reduced WIT, fewer complications, and improved preservation of renal function. Additionally, the comparison of RAPN with other methods of partial nephrectomy underscores its potential as a gold standard approach for managing small renal masses, while further advancements such as zero-ischemia nephrectomy continue to shape the landscape of nephron-sparing surgery. As robotic technology and minimally invasive techniques continue to advance, they are expected to play an increasingly vital role in urological practice, ultimately benefiting patient care and outcomes.

Technological advancements underscore the growing interest and significance of RAPN in the context of partial nephrectomy. Furthermore, many studies indicate that compared to LPN, RAPN is characterized by a reduced WIT, lower estimated blood loss (EBL), a lower conversion rate, and reduced overall mortality.

RAPN seems to be a better option than LPN when it comes to intraoperative and postoperative complications positive margins, a percentage decrease of latest estimated glomerular filtration rate. Various studies comparing RAPN and LPN were examined. Studies by Benway et al. [22], Aboumarzouk et al. [23], Cacciamani et al. [24], Wu et al. [25], Jiang et al. [26], and Choi et al. [28] revealed important insights into perioperative outcomes and differences between the two surgical methods. Overall, RAPN demonstrated advantages over LPN in warm ischemia time, conversion rate, overall mortality, operative time, and blood loss. However, some studies, such as the meta-analysis by Jiang et al. [26], suggested that the differences in EBL may vary depending on the complexity of kidney tumors. Further investigation is warranted to comprehensively assess the outcomes and efficacy of both techniques.

Studies such as Cacciamani's et al. [24] have shown RAPN to be superior to OPN in various perioperative outcomes, including reduced blood loss, complications, hospital stay, and overall mortality. Xia et al. [45] conducted a systematic review and meta-analysis, demonstrating RAPN's advantages over OPN in terms of postoperative complications, transfusion rates, blood loss, and hospital stay. Additionally, Rosiello et al. [46] compared RAPN and OPN in frail patients, finding RAPN to predict lower risks of complications, transfusions, and non-home-based discharge. These findings suggest that RAPN may offer several benefits over OPN, warranting further investigation and comparison between the two techniques.

The off-clamp RAPN showed positive outcomes with no complications, shorter operative time, higher EBL, and smaller decrease in eGFR compared to on-clamp technique. RAPN without clamping with minimal margin was technically feasible and resulted in similar reduction in eGFR but significantly less occurrence of CKD stage >3. Zero-ischemia technique in RAPN or LPN showed no significant differences in kidney function changes. LPN and RAPN with zero ischemia had similar functional outcomes after three months. Off-clamp RAPN had significantly higher operative time, lower blood loss, lower risk of postoperative blood transfusion, higher postoperative eGFR levels, higher tumor size, lower resection time, higher risk of postoperative complications, higher risk of acute kidney injury, and higher risk of postoperative positive surgical margin compared to on-clamp RAPN [39-43].

In the future, the use of robots in surgery will constitute an increasing percentage, and further development of robotic technology as well as better surgical training system and artificial intelligence (AI) will significantly improve surgical techniques. The integration of AI with computer vision algorithms shows promise in obtaining accurate and automated three-dimensional (3D) models for surgical planning in challenging RAPN. The use of AI in medical image analysis has enormous potential in tissue/organ classification and segmentation, leading to the automatic and repetitive generation of 3D models. The AI-based Hyper Accuracy Three-dimensional (HA3D®) models, created through the integration of AI and computer vision approach were found to be accurate and useful in preoperative planning and intraoperative decision-making in RAPN [47]. The potential of AI is improving surgical planning and decision-making processes in nephron-sparing interventions, which could further improve the patient outcomes when using RAPN.

Conclusion

The evolution of urological surgical techniques has increasingly favored RAPN, for treating renal tumors. RAPN offers advantages such as reduced warm ischemia time, lower complication rates, and improved preservation of renal function compared to traditional methods like laparoscopic and open partial nephrectomy. Studies consistently show RAPN's superiority in perioperative outcomes, including reduced blood loss and shorter hospital stays, particularly in frail patients. Advances in artificial intelligence integrated with robotic systems, such as AI-driven 3D modeling for surgical planning, further enhance the precision and outcomes of RAPN. These developments highlight RAPN's growing role and potential as a standard approach in nephron-sparing surgery.

Disclosure:

Authors' contribution:

Conceptualization: Bartłomiej Ast, Krzysztof Dobrzeniecki

Methodology: Bartłomiej Ast, Igor Piotrowski

Software: Bartłomiej Ast

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Formal Analysis: Bartłomiej Ast, Igor Piotrowski

Investigation: Bartłomiej Ast, Krzysztof Dobrzeniecki

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