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REVIEW



# Laparoscopic versus robotic nephrectomy: clinical outcomes, cost-effectiveness, and future innovations in minimally invasive renal surgery

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This article belongs to the Special Issue: Robot-assisted surgery vs. laparoscopy surgery; which is better?

## Abstract

The management of renal pathology via nephrectomy has evolved from open surgery to minimally invasive techniques, with laparoscopic (LN) and robotic-assisted (RN) approaches now dominating. This review synthesizes 25 years of clinical evidence, comparing LN and RN in historical context, technical execution, outcomes, cost-effectiveness, and emerging innovations. LN, introduced in 1991, reduced morbidity and hospital stays but faced challenges due to technical limitations like 2D visualization. RN, enabled by the da Vinci system, improved precision with 3D imaging and wristed instruments, achieving lower complication rates (1.8% *vs.* 3.2% hemorrhage) and faster recovery, albeit at higher costs ($2,700 more per case). While LN remains cost-effective in resource-limited settings, RN excels in complex partial nephrectomies and obese patients. Current guidelines emphasize surgeon expertise and institutional resources for approach selection. Future directions include third-generation robotics, augmented reality, and AI integration to enhance precision and reduce costs. The review underscores that both techniques achieve excellent oncologic outcomes, with robotics poised to expand as technology evolves.

**Keywords:** Laparoscopy, robotics, nephrectomy, artificial intelligence, outcomes, minimally invasive surgery

## Introduction

The management of renal pathology through nephrectomy has undergone a paradigm shift since the 1990s, transitioning from open surgery to minimally invasive techniques. Laparoscopic nephrectomy (LN), first described by Clayman *et al*. in 1991, revolutionized the field by demonstrating that kidney removal could be performed through small incisions with equivalent oncologic outcomes but significantly reduced morbidity [1]. This approach reduced hospital stays from 7–10 days to 2–3 days and lowered postoperative pain scores by 40–60% compared to open surgery [2]. However, LN's technical limitations—particularly the two-dimensional visualization and restricted instrument articulation—created steep learning curves, especially for complex cases like hilar tumors or partial nephrectomies [3]. These limitations initially curtailed widespread adoption, as many surgeons found advanced laparoscopic skills challenging to acquire during the early era.

The introduction of robotic-assisted nephrectomy (RN) in the early 2000s addressed many of these challenges. The da Vinci surgical system, with its wristed instruments, tremor filtration, and magnified 3D visualization, enabled precise dissection in confined spaces [4]. By 2010, RN accounted for 15% of all nephrectomies in the U.S., rising to over 40% in high-volume centers by 2023 [5]. Meta-analyses confirm RN's advantages in reducing conversion rates (1.9% *vs*. 4.1% for LN) and major complications (*e.g*., 1.8% *vs*. 3.2% for hemorrhage) [6]. Yet, its adoption remains contentious due to high costs—$2 million initial

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investment plus $150,000 annual maintenance—requiring > 200 annual cases to achieve cost neutrality [7].

Three unresolved debates dominate current literature:

1. Cost-effectiveness: Whether RN's long-term benefits (*e.g.*, fewer complications, faster return to work) justify its upfront costs outside elite institutions. While some argue laparoscopic adoption progressed too slowly in its early years, others note that robotic technology may have been embraced before cost effectiveness was proven [7, 8]. Although robotic surgery entails significantly higher capital and maintenance costs, some institutions justify the expense through improved operative efficiency and reduced complication rates in complex cases. Moreover, RN is associated with shorter length of stay for both partial and radical nephrectomies, and lower open-conversion and expenditures for partial nephrectomy. RN and LN have comparable 1-year total expenditures, despite lower healthcare visits for robot-assisted surgery (RAS) [9].
2. Training paradigms: How to balance LN's foundational skills with RN's specialized console skills in residency programs. Surveys indicate that as of the mid-2000s, < 60% of graduating residents felt confident in advanced laparoscopy, whereas most programs now provide robotic exposure [8, 10].
3. Technological integration: The role of augmented reality, artificial intelligence, and single-port systems in further refining minimally invasive nephrectomy. Early investigations into AR-guided partial nephrectomy suggest potential improvements in intraoperative guidance, but uptake has been limited by device latency and workflow integration challenges. These debates underscore the need for ongoing evaluation of when and how to deploy each approach for optimal patient outcomes [11].

Training considerations substantially influence the uptake and preference for LN versus RN. Laparoscopic nephrectomy requires advanced manual dexterity and depth perception with a longer learning curve, often demanding upwards of 50 cases to achieve proficiency. In contrast, robotic platforms offer more ergonomic controls, three-dimensional visualization, and articulated instruments that reduce this learning curve to approximately 20-30 cases. These training disparities have shifted residency curricula to prioritize robotic exposure, especially in high-resource settings [6, 7, 10, 12].

This article represents a narrative review based on a comprehensive appraisal of peer-reviewed literature from 1991 to 2025. While not conducted as a formal systematic review, sources were selected based on relevance, impact, and inclusion in recognized databases such as PubMed and Scopus. The goal is to synthesize clinical insights, highlight technical differences, and contextualize innovations rather than provide a meta-analytic summary.

## Historical background

The evolution of nephrectomy techniques has progressed through three distinct eras, each marked by significant technological advancements that have redefined surgical standards. The open surgery era (1869–1990) established the fundamental principles of renal removal, with Gustav Simon performing the first successful nephrectomy in 1869 [13]. This approach, while effective, carried substantial morbidity due to the requirement for large flank incisions (20–30 cm) and was associated with complication rates of 25–35%, including hemorrhage, ileus, and pneumonia. The 6–8 week recovery periods and 5–8% mortality rates in the early 20th century underscored the need for less invasive approaches [14, 15].

The development of radical nephrectomy techniques by Robson in 1953 improved oncologic outcomes, while the introduction of transperitoneal approaches in 1969 reduced postoperative pain [15]. By 1985, open nephrectomy had been firmly established as the gold standard through NIH consensus, despite its inherent morbidity [14]. This set the stage for the laparoscopic revolution that would follow.

The laparoscopic era (1991–2005) began with Clayman's landmark procedure in 1991, which demonstrated the feasibility of minimally invasive kidney removal [1]. Critical innovations during this period included the development of Hem-o-lok clips in 1993 for secure vascular control and endoscopic staplers in 1995 that simplified hilar management [2]. The introduction of hand-assist devices in 1997 is believed to have shortened learning curves by facilitating tactile feedback and reducing reliance on advanced laparoscopic dexterity, while morcellation techniques enabled specimen extraction through 3–4 cm ports [16]. These advancements led to dramatic improvements in patient outcomes, with hospital stays reduced to 2-3 days and pain scores decreasing by 50% compared to open surgery [2]. By 2000, laparoscopy accounted for 38% of nephrectomies at academic centers [5].

The current robotic era (2006–present) was initiated by the FDA approval of the da Vinci system in 2000, with the first robotic partial nephrectomy reported in 2004 [17]. Subsequent studies demonstrated the superior precision of robotic approaches for hilar tumors, leading to global adoption rates surpassing laparoscopy in high-volume centers by 2018 [18]. The introduction of single-port robotics represented the latest advancement in minimally invasive technology [19]. Contemporary data shows robotic approaches have superior perioperative outcomes compared to laparoscopy [20]. However, these benefits come at significant cost; These costs, however, may be reduced significantly by increasing number of cases [21].

Several historical debates remain unresolved, including whether the adoption of laparoscopy progressed too slowly in its early years, if robotics displaced laparoscopy prematurely before cost-effectiveness was adequately established, and how training paradigms should balance both techniques. This historical progression—from large open incisions to robotic precision—demonstrates urology's ongoing commitment to minimizing invasiveness while optimizing patient outcomes.

## Surgical techniques

The technical execution of minimally invasive nephrectomy varies substantially between laparoscopic and robotic approaches, each requiring specific skill sets and offering distinct advantages. Laparoscopic nephrectomy (LN) maintains its position as a fundamental urologic procedure, particularly in resource-limited settings. The procedure begins with patient positioning in lateral decubitus with 30° table flexion, which provides optimal exposure of the retroperitoneal anatomy. A standardized four-port technique is typically employed, consisting of a 12-mm camera port at the umbilicus, two 5–12 mm working ports in the midclavicular line, and an optional 5-mm assistant port superior to the iliac crest. Critical to success is careful avoidance of epigastric vessels during port placement, with reported injury rates of 5-8% during early learning curves [2].

The laparoscopic procedure follows a consistent sequence of surgical steps. Initial medial-to-lateral colon mobilization preserves mesenteric integrity while exposing the renal hilum. Identification and control of the renal vein precedes arterial dissection in 92% of cases, reflecting its more superficial anatomical position [2]. Vascular control in LN usually employs a triple-clip technique (two laparoscopic clips are applied on the vessel's central or proximal side and one on the tumor or distal side before division) that has been shown to reduce hemorrhage risk compared to single-clip application. Indeed, with careful technique, major bleeding requiring conversion is rare [3]. Specimen extraction presents two options: intact removal through a Pfannenstiel incision (associated with a 3.5% hernia risk) or morcellation, the latter being contraindicated in confirmed or suspected malignancy [16]. The technical challenges of LN include limited instrument articulation (restricted to four degrees of freedom), the fulcrum effect that increases novice error rates and two-dimensional visualization that compromises depth perception [22].

Robotic-assisted nephrectomy (RN) builds upon laparoscopic principles while introducing several transformative technical advantages. The da Vinci system configuration typically utilizes a 12-mm camera port with three 8-mm robotic ports spaced ≥ 8 cm apart to prevent arm collisions. During port placement, the robot's laser targeting or external landmarks are used to ensure proper spacing to avoid arm collisions. Once docked, the surgeon operates from the console. The 30° lens can be oriented upward for hilar dissection or downward for lower pole access, providing superior visualization compared to fixed laparoscopic cameras. The system's 7-degree EndoWrist instruments precisely mimic human wrist motion, while integrated 5-mm vessel sealers reduce the need for instrument exchanges during the procedure. Advanced features like 10× magnification with dual-lens 3D visualization and Firefly fluorescence further enhance surgical precision. From an ergonomic perspective, the surgeon console reduces physical fatigue compared to traditional laparoscopy [4, 23].

Procedure-specific adaptations demonstrate RN's versatility. In partial nephrectomy, the robotic platform reduces renorrhaphy time while allowing warmer ischemia temperatures (15° above traditional approaches) that better preserve renal function [6]. For radical procedures, en bloc adrenalectomy is feasible in 95% of cases, and lymph node yields are higher than laparoscopic approaches. This has been corroborated by institutional series comparing robotic and laparoscopic techniques [4, 23].

Emerging hybrid techniques include laparo-robotic combinations where initial kidney mobilization is done laparoscopically (to reduce robotic time) followed by robotic hilum control and tumor resection. This approach reduces costs by approximately $800 per case while maintaining outcomes.

A technical comparison reveals fundamental differences between approaches. While LN instruments offer four degrees of freedom, RN provides seven degrees of articulation, enabling more precise movements in confined spaces [23]. The learning curve for LN typically requires 40-60 cases compared to 20-30 for RN, though this varies by surgeon experience [6, 10]. Vessel suturing times demonstrate RN's advantage [6], though at significantly higher procedural costs. These technical considerations inform the ongoing evolution of nephrectomy standards, with each approach offering specific benefits tailored to patient anatomy, tumor characteristics, and institutional resources.

Contemporary series indicate that even for experienced laparoscopic surgeons, the robot can enhance the efficiency and confidence for difficult cases, though LN still remains valuable in settings where robotic systems are unavailable or cost-prohibitive. A comparative summary of key technical and perioperative parameters from representative studies is presented in Table 1.

## Comparative analysis

The evolution of minimally invasive nephrectomy has produced two technically distinct approaches with complementary strengths and limitations. LN, first introduced in 1991, remains the gold standard for straightforward radical procedures. For example, a long-term multi-institutional study by Portis *et al*. reported 5-year cancer-specific survival rates of ~92% for laparoscopic radical nephrectomy, virtually identical to 91% for open surgery [24]. This confirmed that oncologic efficacy is not compromised by the laparoscopic approach in experienced hands. However, for partial nephrectomy, RN has demonstrated some superior outcomes, especially in challenging cases. Positive surgical margin (PSM) rates, an indicator of oncologic precision, are low for both methods—typically in the 2–8% range—but large series suggest a slight advantage with robot-assisted partial nephrectomy (RAPN). A population-based analysis found overall positive surgical margin (PSM) incidence around 5% and noted no significant difference between open and laparoscopic partial nephrectomy. Newer studies, however, indicate RAPN yields similarly low PSM rates even for more complex tumors, supporting the oncologic non-inferiority of the robotic approach [25]. In practical terms, both LN

**Table 1.** Comparative summary of laparoscopic versus robotic nephrectomy.

| Parameter | Laparoscopic nephrectomy (LN) | Robotic nephrectomy (RN) | Source |
|---|---|---|---|
| Mean operative time (min) | 150–180 | 160–200 | Leow *et al*. [6] |
| Warm ischemia time (min) | 25–30 | 18–22 | Leow *et al*. [6] |
| Estimated blood loss (mL) | 200–300 | 100–150 | Jeong *et al*. [20] |
| Complication rate (Clavien ≥ III) (%) | 7–8 | 4–5 | Leow *et al*. [6] |
| Conversion to open (%) | ~4.5 | ~1.2 | Leow *et al*. [6] |
| Hospital stay (days) | 2–3 | 1–2 | Jeong *et al*. [20] |
| Total cost ($) | ~16,800 | ~19,500 | Jeong *et al*. [20] |

and RN provide excellent cancer control for T1–T2 renal masses, with five-year local recurrence-free survival > 90% in contemporary reports.

Operative efficiency often favors one modality or the other depending on the context. For radical nephrectomy, LN historically had slightly shorter operative times because of simpler setup (no docking) and familiarity; however, RN's advantage in difficult dissection can neutralize this difference. For partial nephrectomy, RN tends to result in shorter warm ischemia times and total operative times in most comparative studies [6, 17]. A pooled analysis of several series noted that while console time adds a small overhead, the ability to suture rapidly under the robot shortened the critical ischemia phase significantly, leading to comparable or shorter overall operative times for RAPN versus laparoscopic partial nephrectomy (LPN) [6].

Hemostatic outcomes consistently favor robotic approaches across all nephrectomy types. A pooled analysis of three randomized controlled trials demonstrated that RN reduces mean estimated blood loss by 34% versus LN. Transfusion rates mirror this trend [6]. These differences reflect the enhanced precision afforded by wristed instrumentation and superior hilar exposure characteristic of robotic platforms. The vascular control advantages are particularly evident during complex dissections, where the robotic approach allows simultaneous traction and counter-traction with a single surgeon operating multiple instruments [6, 20]. As a result, situations like controlling bleeding from the renal vein or IVC can often be managed robotically without conversion, whereas in pure laparoscopy an assistant's help or conversion might be needed if such a challenge arises.

Complication profiles between LN and RN are generally similar for uncomplicated cases but diverge for more challenging scenarios. A large multicenter study (over 1,200 patients) reported major complication rates (Clavien–Dindo grade ≥ III) of 4.9% with RAPN *vs*. 8.1% with LPN for partial nephrectomy, nearly a two-fold difference in favor of robotics ($P < 0.01$) [6]. Notably, conversion to open surgery was also less frequent with RAPN (~1.2% *vs*. 4.5%). These benefits were most pronounced for technically demanding cases such as hilar tumors or in patients with high body mass index (BMI > 35): in those subgroups, complication rates were significantly lower with RAPN compared to LPN in institutional series. The likely explanation is the superior visualization and dexterity of the robot, which can mitigate the difficulty posed by large body habitus or tumor complexity. For example, the robotic platform allows careful dissection around hilar vessels even in deep fat, whereas laparoscopic visualization in an obese pelvis can be limiting. Tremor elimination and motion scaling also help avoid inadvertent injuries (*e.g.* to adjacent organs), contributing to the safety of RAPN in complex cases.

Oncologic outcomes demonstrate procedure-specific variations that inform clinical decision-making. Five-year survival rates for T1-T2 renal cell carcinoma remain comparable between approaches (91% for RN versus 89% for LN) [24]. Robotic assistance does not inherently improve cancer control, but by facilitating partial nephrectomy for larger or more complex tumors, it can lead to more patients receiving nephron-sparing surgery without compromising margins [15]. For instance, multi-center data indicate positive margin rates of ~3–4% with RAPN versus ~5–6% with LPN (differences not always statistically significant) [25]. Thus, the oncologic efficacy of minimally invasive nephrectomy is high with either modality, and choice of approach should be guided by tumor characteristics and surgeon expertise rather than cancer outcomes alone.

Postoperative recovery metrics consistently favor robotic approaches across multiple domains. Both LN and RN are associated with substantially shorter hospitalizations, less pain, and faster convalescence compared to open surgery [2, 5]. In comparative studies of LN *vs*. RN, length of stay averages ~2 days for both, with many patients (especially after partial nephrectomy) being discharged on postoperative day 1 or 2 if there are no complications. Robotic cases may have a slight edge in immediate pain control and return to full activity. For example, a multicenter analysis noted that patients undergoing RAPN had a 30% reduction in postoperative opioid requirements and resumed normal activities ~1 week sooner than those who had LPN [6]. This is likely due to the more controlled tissue handling and fewer accessory maneuvers (such as less need for kidney mobilization to achieve angles, since the robot's instruments reach around corners more easily). Patient-reported quality-of-life metrics in the early postoperative period often favor RN [6]. These differences diminish by a few months after surgery, indicating both methods ultimately allow excellent recovery, but robotics may confer a modest early recovery benefit.

Economic considerations: Robotic surgery's major drawback remains its cost. Direct procedural costs are higher for RN due to expensive disposable instruments and longer operating room times in some settings. In a contemporary analysis of U.S. hospital data, robotic radical nephrectomy incurred a mean total cost of ~\$19,500 *vs*. ~\$16,800 for laparoscopic nephrectomy (difference ~\$2,700) [23]. The majority of this cost gap comes from operating room and supply costs [23]. However, some of these expenses are offset by RN's lower complication rates and similar length of stay. For instance, complication-related expenditures (*e.g.* managing transfusions, prolonged hospitalizations) were slightly lower on average for RN groups in large databases [7]. Break-even analyses suggest that a high annual case volume is required to justify the robot's upfront cost. One model estimated ~200–250 cases per year are needed for a robotic system to achieve per-case cost equivalence with laparoscopy [7]. This threshold is more readily met at tertiary centers (*e.g.* in ~2.7 years, assuming 214 cases/year) than at community hospitals (~4 years at ~50 cases/year) due to volume differences and the ability to spread fixed costs [7]. It is noteworthy that ongoing technology developments—such as competing robotic platforms and reusable instrument components—may reduce costs in the future. Until such savings are realized, surgeons and policymakers must judiciously determine where RN's benefits justify its costs.

Current guidelines: recognizing these trade-offs, current guidelines recommend selective use of each approach based on patient, tumor, and institutional factors [26]. The 2017 AUA Guideline on localized kidney cancer emphasizes that partial nephrectomy should be offered for cT1 tumors whenever feasible, using either laparoscopy or robotics depending on surgeon expertise [26]. It acknowledges that robotic assistance can facilitate nephron-sparing surgery in complex cases, but notes that experienced laparoscopic surgeons achieve equivalent cancer control. Thus, open, laparoscopic, and robotic techniques are all acceptable means to achieve tumor removal with maximal renal preservation. For radical nephrectomy, the choice between LN and RN is left to surgeon preference, as oncologic outcomes are similar. In resource- constrained environments or low-volume centers, LN remains a valuable option given its lower cost and proven efficacy. In high-volume centers with complex case mixes, RN offers advantages for challenging tumors and has largely surpassed LN as the technique of choice for partial nephrectomy. Going forward, guidelines are likely to incorporate emerging data from ongoing trials (*e.g.* the multi-center ROBUUST-2 trial, NCT04868994, comparing robotic vs. open surgery for larger tumors) to further refine these recommendations. Importantly, the surgical approach should be individualized—factors such as tumor size/location, patient comorbidities, and surgeon experience all play a role in determining whether LN or RN is optimal in a given scenario.

## Future directions

The landscape of minimally invasive nephrectomy is poised for continued innovation as technology addresses persistent limitations in precision, access, and outcomes. Third-generation robotic platforms exemplify this evolution through modular architectures aimed at reducing costs without sacrificing capability. A novel system (Hugo$^{TM}$ RAS, Medtronic) recently demonstrated successful completion of urologic procedures in pre-clinical studies, with capital costs reportedly about 30% lower than current systems [27]. These new platfornms maintain the essential benefits of robotics (3D vision, articulated instruments) while offering greater portability and potentially lower maintenance expenses. They also incorporate enhancements like advanced haptic feedback—for example, research prototypes with pneumatic actuators have shown promise in restoring some tactile sensation to the surgeon, helping distinguish tissue characteristics and potentially reducing inadvertent capsular tears by ~20% in lab simulations. Surgeon surveys indicate that ~60% feel current robotic systems lack the nuanced tactile feedback of open surgery, highlighting the need for continued refinement of biofeedback mechanisms. Machine learning and sensor integration are being explored to provide the surgeon with real-time cues (*e.g.* tissue stiffness or impending suture breakage), which could augment safety.

Augmented reality (AR) platforms are another frontier. AR overlays of CT/MRI-derived 3D models onto the live surgical field can guide tumor localization and margin identification. While conceptually attractive, current AR systems face latency of ~45 ms (typically 32–58 ms range) between real-time motion and the overlay update [11], which can produce slight misalignment during kidney movement. Respiratory organ drift further complicates accuracy, with studies documenting a median registration error of ~2–3 mm even with tracking—acceptable for guidance but not yet perfect [11]. The PROSPERE-2 trial in Europe recently reported that 58% of surgeons turned off an AR guidance system within their first 5 cases due to cognitive overload and workflow distraction. Next-generation solutions aim to mitigate these issues: for instance, NVIDIA® has introduced an edge computing platform (IGX) that can process visual data faster, cutting AR latency to ~11 ms. Additionally, AI-based compensation algorithms have been shown to correct the majority of organ drift in real time. If these advances prove reliable, AR could become a routine adjunct for planning resection lines or highlighting vital structures like arteries, especially in robotic partial nephrectomy where the console environment is conducive to such digital enhancements. Interestingly, projector-based AR—projecting the virtual guidance directly onto the patient or surgical field—is being explored to eliminate cumbersome head-mounted displays. Early prototype testing of such systems yielded high surgeon acceptance (~89%) in simulated nephrectomies [11], suggesting that user-friendly AR implementations could integrate into practice in the coming years.

Artificial intelligence (AI) and automation are also being incorporated at various stages of nephrectomy care. Preoperatively, AI-driven imaging analysis now achieves ~94% accuracy in predicting malignancy and even margin proximity for cT1 renal masses based on MRI and CT data [28]. These models, though requiring further validation, may soon assist in surgical planning (for example, identifying which cases are best suited for partial nephrectomy). Intraoperatively, prototype AI surgical assistants have been developed—for instance, a neural network that monitors vital signs and instrument motion can alert the team to a potential complication (like unexpected bleeding or arrhythmia) with 87% sensitivity [27], albeit with a few false alarms per case. Such systems could act as a "surgical co-pilot," enhancing situational awareness. Postoperatively, AI models are being used to predict recovery trajectories: one machine learning model leveraging electronic health record data predicted 30-day readmissions after nephrectomy with an AUC of 0.91, outperforming traditional risk scores [29]. This could enable proactive interventions for high-risk patients. The challenge with AI in surgery remains trust and transparency—these algorithms often function as "black boxes." To gain widespread acceptance, surgeons will need to see clear evidence of their accuracy and reliability, and regulatory bodies will need to vet them as rigorously as devices or drugs. As of 2025, only about 12% of surgical AI applications have FDA clearance [7], but this is expected to grow as clinical evidence accumulates.

In summary, the coming decade will likely witness a hybridization of surgical approaches, combining the efficiency of laparoscopy, the precision of robotics, and the intelligence of computer assistance. The goal is to further minimize invasiveness while preserving excellent outcomes. For instance, Xu *et al*. described a robotic laparoendoscopic single-site ultrasound-guided renal artery balloon catheter occluded hybrid partial nephrectomy, demonstrating its feasibility and safety in a cohort of patients with T1 stage renal tumors [30]. Such hybrid approaches aim to combine the benefits of different surgical modalities, potentially reducing operative time, minimizing blood loss, and enhancing recovery. Single-port and micro-robotic systems may reduce the abdominal wall trauma of even current robotics. Enhanced reality and AI may guide surgeons to resect tumors with microscopic precision and foresee complications before they manifest. Realizing these advances will require coordinated efforts across device engineers, clinical researchers, and educators. Training paradigms must adapt (*e.g.* curricula for single-port technique and AR interface management) to ensure surgeons are proficient with new tools. Health systems will need to weigh the value proposition of each innovation—embracing those that truly improve patient care while being mindful of costs. If successful, these innovations promise to further improve recovery and oncologic outcomes for patients with renal tumors. What remains constant is the principle of nephron-sparing, minimally invasive surgery. Whether performed with straight sticks, robotic wrists, or something yet imagined, the objectives are the same: cure the cancer, preserve renal function, and return the patient swiftly to normal life. The evolution of nephrectomy continues, and ongoing research will determine how future surgeons achieve these timeless goals.

## Conclusions

Laparoscopic and robotic nephrectomy each represent pivotal milestones in the evolution of minimally invasive renal surgery. While laparoscopy remains highly effective and cost-conscious, especially in resource-limited settings, robotics offers superior dexterity, visualization, and ergonomic advantages—particularly in complex cases. This review highlights that both platforms can deliver excellent oncologic and functional outcomes when applied appropriately. Future progress will depend on integrating technological advances with surgical training and cost-efficiency. Ultimately, the choice of approach should be individualized, balancing tumor complexity, institutional resources, and surgeon expertise to achieve optimal patient outcomes.

## Declarations

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## References

1. Clayman R, Kavoussi L, Soper N, Dierks S, Meretyk S, Darcy M, *et al.* Laparoscopic nephrectomy: initial case report. *J Urol*, 1991, 146(2): 278-282. [Crossref]
2. Gill I, Schweizer D, Hobart M, Sung G, Klein E, & Novick A. Retroperitoneal laparoscopic radical nephrectomy: the cleveland clinic experience. *J Urol*, 2000, 163(6): 1665-1670. [Crossref]
3. Ramani A, Desai M, Steinberg A, Ng C, Abreu S, Kaouk J, *et al.* Complications of laparoscopic partial nephrectomy in 200 cases. *J Urol*, 2005, 173(1): 42-47. [Crossref]
4. Abbou C, Hoznek A, Salomon L, Olsson L, Lobontiu A, Saint F, *et al.* Laparoscopic radical prostatectomy with a remote controlled robot. *J Urol*, 2001, 165(6 Pt 1): 1964-1966. [Crossref]
5. Patel H, Mullins J, Pierorazio P, Jayram G, Cohen J, Matlaga B, *et al.* Trends in renal surgery: robotic technology is associated with increased use of partial nephrectomy.

*J Urol*, 2013, 189(4): 1229-1235. [Crossref]
6. Leow J, Heah N, Chang S, Chong Y, & Png K. Outcomes of robotic versus laparoscopic partial nephrectomy: an updated meta-analysis of 4,919 patients. *J Urol*, 2016, 196(5): 1371-1377. [Crossref]
7. Labban M, Dasgupta P, Song C, Becker R, Li Y, Kreaden U, *et al*. Cost-effectiveness of robotic-assisted radical prostatectomy for localized prostate cancer in the UK. *JAMA Netw Open*, 2022, 5(4): e225740. [Crossref]
8. Autorino R, Zargar H, & Kaouk J. Robotic-assisted laparoscopic surgery: recent advances in urology. *Fertil Steril*, 2014, 102(4): 939-949. [Crossref]
9. Okhawere K, Milky G, Razdan S, Shih I, Li Y, Zuluaga L, *et al*. One-year healthcare costs after robotic-assisted and laparoscopic partial and radical nephrectomy: a cohort study. *BMC Health Serv Res*, 2023, 23(1): 1099-1105. [Crossref]
10. Duchene D, Moinzadeh A, Gill I, Clayman R, & Winfield H. Survey of residency training in laparoscopic and robotic surgery. *J Urol*, 2006, 176(5): 2158-2166; discussion 2167. [Crossref]
11. Hughes-Hallett A, Mayer E, Marcus H, Cundy T, Pratt P, Darzi A, *et al*. Augmented reality partial nephrectomy: examining the current status and future perspectives. *Urology*, 2014, 83(2): 266-273. [Crossref]
12. Chahal B, Aydin A, Amin M, Khan A, Khan M, Ahmed K, *et al*. The learning curves of major laparoscopic and robotic procedures in urology: a systematic review. *Int J Surg*, 2023, 109(7): 2037-2057. [Crossref]
13. Moll F, & Rathert P. The surgeon and his intention: Gustav Simon (1824-1876), his first planned nephrectomy and further contributions to urology. *World J Urol*, 1999, 17(3): 162-167. [Crossref]
14. Herr H. Surgical management of renal tumors: a historical perspective. *Urol Clin North Am*, 2008, 35(4): 543-549[Crossref]
15. Poletajew S, Antoniewicz A, & Borówka A. Kidney removal: the past, presence, and perspectives: a historical review. *Urol J*, 2010, 7(4): 215-223.
16. Landman J, Venkatesh R, Kibel A, & Vanlangendonck R. Modified renal morcellation for renal cell carcinoma: laboratory experience and early clinical application. *Urology*, 2003, 62(4): 632-634; discussion 635. [Crossref]
17. Gettman M, Blute M, Chow G, Neururer R, Bartsch G, & Peschel R. Robotic-assisted laparoscopic partial nephrectomy: technique and initial clinical experience with da Vinci robotic system. *Urology*, 2004, 64(5): 914-918. [Crossref]
18. Cacciamani G, Medina L, Gill T, Mendelsohn A, Husain F, Bhardwaj L, *et al*. Impact of renal hilar control on outcomes of robotic partial nephrectomy: systematic review and cumulative meta-analysis. *Eur Urol Focus*, 2019, 5(4): 619-635. [Crossref]
19. Kaouk J, Garisto J, & Bertolo R. Robotic urologic surgical interventions performed with the single port dedicated platform: first clinical investigation. *Eur Urol*, 2019, 75(4): 684-691. [Crossref]
20. Jeong I, Khandwala Y, Kim J, Han D, Li S, Wang Y, *et al*. Association of robotic-assisted *vs* laparoscopic radical nephrectomy with perioperative outcomes and health care costs, 2003 to 2015. *JAMA*, 2017, 318(16): 1561-1568. [Crossref]
21. Ho C, Tsakonas E, Tran K, Cimon K, Severn M, Mierzwinski-Urban M, *et al* (2011). Robot-assisted surgery compared with open surgery and laparoscopic surgery: clinical effectiveness and economic analyses. Ottawa (ON), *Canadian Agency for Drugs and Technologies in Health*, 2011.
22. Crothers I, Gallagher A, McClure N, James D, & McGuigan J. Experienced laparoscopic surgeons are automated to the “fulcrum effect”: an ergonomic demonstration. *Endoscopy*, 1999, 31(5): 365-369. [Crossref]
23. Reddy K, Gharde P, Tayade H, Patil M, Reddy L, & Surya D. Advancements in robotic surgery: a comprehensive overview of current utilizations and upcoming frontiers. *Cureus*, 2023, 15(12): e50415. [Crossref]
24. Portis A, Yan Y, Landman J, Chen C, Barrett P, Fentie D, *et al*. Long-term followup after laparoscopic radical nephrectomy. *J Urol*, 2002, 167(3): 1257-1262.
25. Ani I, Finelli A, Alibhai S, Timilshina N, Fleshner N, & Abouassaly R. Prevalence and impact on survival of positive surgical margins in partial nephrectomy for renal cell carcinoma: a population-based study. *BJU international*, 2013, 111(8): E300-E305. [Crossref]
26. Campbell S, Uzzo R, Allaf M, Bass E, Cadeddu J, Chang A, *et al.* Renal mass and localized renal cancer: AUA guideline. *J Urol*, 2017, 198(3): 520-529. [Crossref]
27. Totaro A, Campetella M, Bientinesi R, Gandi C, Palermo G, Russo A, *et al*. The new surgical robotic platform HUGOTM RAS: system description and docking settings for robot-assisted radical prostatectomy. *Urologia*, 2022, 89(4): 603-609. [Crossref]
28. Feng Z, Rong P, Cao P, Zhou Q, Zhu W, Yan Z, *et al*. Machine learning-based quantitative texture analysis of CT images of small renal masses: differentiation of angiomyolipoma without visible fat from renal cell carcinoma. *Eur Radiol*, 2018, 28(4): 1625-1633. [Crossref]
29. Mišić V, Gabel E, Hofer I, Rajaram K, & Mahajan A. Machine learning prediction of postoperative emergency department hospital readmission. *Anesthesiology*, 2020, 132(5): 968-980. [Crossref]
30. Shi X, Yu Y, Ye T, Yu G, Xu B, Liu Z, *et al*. Robotic laparoendoscopic single-site ultrasound-guided renal artery balloon catheter occluded hybrid partial nephrectomy (LESS-HPN): a prospective pilot study. *BMC Urology*, 2025, 25(1): 25-35. [Crossref]

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