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Technological evolution in urology: assessing laparoscopic and robotic surgery

José M. Campero[a], Ricardo Mora[a], Juan A. Fulla[a,b,*]

[a] *Clínica MEDS, Santiago, Chile.*
[b] *Department of Urology, University of Chile, Santiago, Chile.*

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

Abstract

Background: Minimally invasive techniques have revolutionized urological surgery, offering significant benefits over open surgery. This study compares the efficacy, cost-effectiveness, and accessibility of laparoscopic and robotic-assisted surgical techniques in urology.
Methods: We conducted a systematic review of the current literature of studies comparing outcomes of laparoscopic and robotic-assisted surgery in urology. Key performance indicators such as operative time, precision, complication rates, and learning curves were assessed.
Results: Both techniques demonstrate high efficacy, with robotic-assisted surgery offering greater precision and control, particularly in complex procedures. However, the higher costs associated with robotic systems impact their accessibility and adoption, particularly in resource-limited settings. Laparoscopy remains cost-effective and widely accessible, continuing to improve with technological advances in instrumentation and imaging.
Conclusion: Robotic-assisted surgery enhances precision but is limited by high cost Laparoscopy remains a cost-effective, accessible alternative with evolving capabilities. Ongoing innovations in laparoscopic instruments and techniques is critical to maintaining its competitive edge. Healthcare systems must consider both economic and clinical factors when deciding which technologies to implement, ensuring that the benefits of minimally invasive surgery are available to all patients.
Keywords: Minimally invasive surgery, laparoscopy, robotic-assisted surgery, urology, surgical outcomes

Introduction

The landscape of urological surgery has been profoundly influenced by the adoption of minimally invasive techniques, primarily laparoscopy and robotic-assisted surgery. These methods not only enhance surgical precision and patient outcomes, but also redefine postoperative recovery paradigms. This manuscript aims to compare the efficacy, cost-effectiveness, and broader accessibility of laparoscopic and robotic-assisted techniques in urology. Understanding these nuances is crucial as healthcare systems globally strive to optimize outcomes while managing costs.

This analysis delves into how each technology adapts to the challenges posed by complex urological conditions and the economic implications influencing their adoption across diverse healthcare landscapes. Ongoing advances in surgical technology and instrumentation, along with critical assessment of their economic viability, underscore a pivotal era of innovation in urological surgery.

Methodology

For the development of this thematic review, inclusion criteria were established encompassing primary and secondary studies focusing on the efficacy, safety, economic feasibility, and clinical outcomes of laparoscopic and robotic surgery in urology. Studies that did not provide

* Corresponding author: Juan Fulla, MD
Mailing address: University of Chile, Avenida Santa Rosa 1234, Santiago, Chile.
Email: juanfulla@gmail.com
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direct comparative data or that focused solely on surgical technique without addressing postoperative outcomes were excluded.
The literature search was conducted in databases such as PubMed, EMBASE, and Web of Science using combinations of key terms such as "laparoscopic surgery", "robotic surgery", "urology", "cost-effectiveness", "clinical outcomes", "surgical training", and "technology adoption". The search strategy was supplemented by reviewing the bibliographic references of selected studies to identify additional relevant works. The review process focused on synthesizing the available evidence, discriminating between quantitative and qualitative data to provide an equitable and detailed analysis. This synthesis aimed not only to highlight technical and outcome differences between the two modalities, but also to identify trends in technological adoption and its sustainability in different socioeconomic contexts, especially in regions with limited resources. Data interpretation was conducted with a focus on clinical relevance and applicability in medical decision making.

Historical overview of laparoscopic and robotic surgery in urology

Laparoscopy, derived from the ancient Greek "laparos" meaning "flank or abdomen", highlights the surgical technique of accessing the abdominal cavity via small incisions, closely tied to its etymological roots [1, 2]. Initiated in 1901 by George Kelling using Nitze's cystoscope, laparoscopy evolved during the late 20th century with significant contributions from Kurt Semm in the development of operative instruments and techniques [3, 4]. The first laparoscopic nephrectomy, performed by Dr. Ralph V. Clayman in 1990, marked a critical advance over traditional open surgery, setting the stage for the proliferation of minimally invasive procedures in urology [5, 6].
Parallelly, the field of robotic surgery in urology, which began in the late 1980s, has seen significant technological advances, notably with the introduction of the da Vinci surgical system in 1997. This system, approved by the FDA, significantly improved the precision and outcomes of urological procedures through enhanced visualization and tissue retraction [7, 8]. The use of the PUMA 560 robotic system for neurosurgical biopsies by Kwoh *et al*. marked the commencement of modern robotic surgery, emphasizing the role of robotics in facilitating remote and precise surgical interventions [9, 10].
These developments in laparoscopic and robotic surgery have not only transformed the landscape of urological surgery but have also set a benchmark for the application of minimally invasive techniques in complex operations, underscoring their critical impact on patient outcomes and the evolution of surgical practice.

Technical description of surgical modalities in laparoscopy and robotics

Laparoscopic surgery typically requires three primary entry points for inserting trocars, which accommodate the camera and surgical instruments, plus one or two accessory ports as needed. The configuration of these ports varies with patient anatomy, surgery type, and surgeon preference [11, 12]. Modern trocars, featuring a transparent design with a universal valve, blunt tip, and fixation to the abdominal wall, reflect significant advances over earlier designs restricted by patents [13]. Innovations such as single-port robots contrast with traditional multi-trocar setups, facilitating specimen extraction through minimal incisions or natural orifices (NOTES) [14].
The da Vinci Surgical System from Intuitive Surgical exemplifies the advances in robotic surgery, comprising a console and cart with three to four robotic arms, which perform tasks ranging from cutting to grasping with high precision. An additional arm controls the 3D cameras, enhancing the surgeon's visualization [15, 16]. Employed in diverse procedures like radical prostatectomy and lung transplantation, the da Vinci System has broadened the scope of minimally invasive surgery, offering more precise, efficient, and less invasive options, thus improving surgical outcomes and reducing recovery times [17, 18].
The evolution from multiport (MP) to single-port (SP) systems in robotic surgery like the da Vinci has sparked debates over their advantages and disadvantages. The SP system, for instance, reduces the incision size to a single 30-40 mm entry, enhancing cosmetic outcomes and lessening postoperative pain, but faces limitations in instrument flexibility and range of motion. These constraints may complicate procedures requiring intricate manipulation and managing intraoperative challenges [19-21].
Emerging competitors in the robotic surgery market are introducing systems like Medtronic's Hugo™ and CMR Surgical's Versius®, which prioritize modularity, compact design, and surgeon ergonomics. However, these newer systems face challenges such as market validation and clinical endorsement compared to the established da Vinci System [22, 23]. This overview encapsulates the current state of laparoscopic and robotic surgical modalities, highlighting their technological progression, clinical applications, and ongoing developments in surgical robotics.

Surgical instruments overview: laparoscopy and robotics

Laparoscopic instruments have evolved significantly from their origins in the late 1700s with Bozzini's "light conductor" to modern technologies incorporating 3D and high-definition optics [24]. Today's instruments include high-definition endoscopes that provide real-time 4K image transmission globally and allow for augmented reality applications, enhancing the surgeon's view with critical physiological data [25]. Traditional instruments like straight scissors and various forceps are designed for specific tasks such as cutting and grasping, while advanced energy devices ensure minimal damage to adjacent tissues [26]. Articulated instruments, like robotic counterparts, offer greater flexibility, aiding in complex procedures without extensive dissection [27].

Robotic surgery, particularly using the da Vinci Surgical System, represents a significant leap in instrument standardization and functionality, closely mirroring traditional laparoscopic approaches [28]. The system's advanced Insite-Vision System delivers a stereoscopic three-dimensional view, enhancing the surgeon's ability to perform precise dissections and reconstruction through small incisions [29]. Instruments on this platform, like the EndoWrist, provide a range of motion that replicates the human hand's dexterity, allowing for intricate maneuvers and precise tissue handling. This design reduces the counterintuitive manipulations often necessary in laparoscopy due to the fulcrum effect of body cavity entry [30].

The da Vinci system's ergonomic design reduces surgeon fatigue by aligning the console controls with natural hand movements, significantly enhancing surgical performance and endurance [31]. This system not only improves the efficiency of procedures like prostatectomies and cystectomies but also broadens the scope of robotic surgery in urology and beyond, setting a new standard for minimally invasive surgery.

In conclusion, the integration of advanced imaging technologies and ergonomic design in both laparoscopic and robotic instruments significantly enhances surgical precision and safety, reflecting substantial progress in surgical practice.

Challenges and Implications in Laparoscopic and Robotic Surgery

Learning curve in surgical proficiency

The concept of the learning curve, initially described in the aviation industry in 1936, relates to the efficiency gains and skill improvements over time [32]. In surgery, the learning curve denotes the period a surgeon takes to become proficient, measured by the reduction in operation time (OT) and estimated blood loss (EBL), although other indicators like surgical margins and ischemia times are equally significant [33].

For laparoscopic radical prostatectomy, proficiency may require handling 40-250 cases to notably reduce OT and EBL [34]. Interestingly, Vickers *et al*. and Hruza *et al*. observed that surgeons with less open surgery experience could adapt to laparoscopic techniques more quickly, indicating a varied learning curve based on prior experience [35]. Similarly, around 22 to 50 cases are needed to decrease OT in laparoscopic partial nephrectomy, with 150 cases needed to achieve optimal surgical margins and minimize complications [36].

In robotic surgery, while general learning metrics like OT and EBL do not show significant early differences compared to laparoscopy, robotic techniques tend to result in lower rates of positive margins and improved early continence [37]. Studies suggest a shorter learning curve for robot-assisted surgeries, particularly when the surgeon has prior experience in robotic or laparoscopic methods [38]. For instance, around 25 cases are needed to reduce operative time (OT) in robotic pyeloplasty, demonstrating the rapid acquisition of competency with robotic systems [34]. Moreover, support from experienced laparoscopic assistants and involvement as a bedside surgeon in robotic surgeries can significantly improve outcomes and expedite the learning process [39]. This highlights the importance of a supportive surgical team and structured training programs in mastering complex surgical procedures.

Technical difficulties and barriers in laparoscopy and robotic surgery

Laparoscopic surgery faces challenges primarily related to limitations in instrument mobility and visual clarity, which are essential for performing complex surgical tasks. Traditional instruments, being straight and rigid, restrict movement, making intricate procedures like suturing and tissue dissection in confined spaces like the pelvis difficult [40]. However, technological advances such as 3D visualization systems and articulating instruments have significantly enhanced depth perception and range of motion, bridging some gaps between traditional laparoscopy and robotic capabilities. These tools allow for more precise manipulation of tissues, particularly in space-constrained surgical environments [41].

Robotic systems, while offering advanced surgical capabilities, come with their own set of challenges. The complexity of these systems requires robust integration of technology and meticulous intraoperative management. Challenges include the coordination of system components and the need for immediate technical support to address mechanical failures during procedures [42]. Moreover, the infrastructure demands for robotic surgery, such as specialized operating room space and ongoing maintenance, impose significant logistical and financial barriers, particularly in resource-limited settings.

A notable limitation of robotic surgery is the absence of tactile feedback, which can hinder the surgeon's ability to gauge the force applied during tissue manipulation. Although advanced visual aids and surgeon experience help mitigate this drawback, the lack of tactile sensation remains a critical issue [43]. Furthermore, the high costs associated with acquiring, maintaining, and training of robotic systems pose substantial challenges. These financial requirements may limit the adoption of robotic surgery, questioning its cost-effectiveness compared to traditional and advanced laparoscopic techniques, especially when clinical outcomes are similar [44, 45].

Overall, while both laparoscopic and robotic surgery continue to advance, addressing these technical difficulties and barriers is crucial for wider adoption and optimization of these surgical modalities.

The integration of robotic systems into the surgical domain is transforming modern urology but also introduces significant interdisciplinary challenges that must be navigated carefully. These systems demand mastery in coordinating robotic limbs and effectively navigating a console interface, which diverges significantly from traditional manual techniques. Such a shift not only impacts the technical execution but may also influence operating times, particularly during the initial learning phases [46].

Infrastructure demands are also critical, as the integration of robotic surgery necessitates comprehensive alterations to operating theater design to accommodate the spatial and functional needs of robotic systems. This includes establishing high-bandwidth networking capabilities essential for data handling and streaming of complex surgical procedures, as well as developing rigorous maintenance protocols to ensure operational readiness and system integrity [47]. One of the inherent limitations of current robotic systems is the absence of haptic feedback, which represents a significant departure from traditional surgery where tactile sensation is integral to the manipulation and assessment of tissues [48].

Robotic-assisted surgery (RAS) poses both economic and operational challenges. The transition from traditional manual practices to RAS requires significant proficiency in robotic coordination and adaptation to console-based operations. These changes can considerably extend operating times due to the steep learning curve associated with mastering these advanced systems [49]. Moreover, the infrastructure must be adapted to support RAS, necessitating not only physical modifications in the operating theaters but also advanced networking for efficient data handling and consistent system maintenance to ensure reliability and safety during procedures [50].

Financial considerations are particularly acute in low- and middle-income countries (LMICs), where resource constraints are compounded by higher incidences of surgical site infections (SSIs) and prolonged hospital stays. Despite these hurdles, the integration of RAS could yield significant benefits, potentially reducing physician burnout, lowering the incidence of SSIs, and shortening the length of hospital stays. Robotic surgery affords surgeons the ergonomic advantage of improved dexterity through articulated instruments that are crucial for performing complex procedures in urology and other specialties. However, these benefits come at the expense of higher costs associated with the deployment of single-use instruments [51, 52].

Disparities in access to RAS in LMICs are exacerbated by several socioeconomic factors, including the prohibitive cost of setting up new robotic platforms and the ongoing expenses related to each surgical procedure. Moreover, training disparities and limitations in network infrastructure further hinder the widespread implementation of robotic surgery [53]. Nevertheless, the long-term feasibility of RAS must be acknowledged, given its potential to reduce postoperative care expenses and enhance patient quality of life. To optimize RAS in LMICs, it could be necessary to devise innovative financial and technical support mechanisms that improve access and leverage robotic surgery to transform surgical care, while also considering the overall cost-effectiveness compared to traditional laparoscopic methods [54].

The financial barriers to robotic surgery are formidable, with high capital investment required for acquisition, ongoing maintenance, and the need for specialized training. These costs make it particularly challenging in resource-limited settings where healthcare funding might be better allocated towards broader public health priorities [55].

Robotic surgical systems are equipped with a surgical arsenal analogous to that found in traditional surgery, yet they introduce a unique set of operational dynamics and financial impacts. These systems primarily use single-use instruments, which, while ensuring sterility and optimal functionality, come at a high cost. This expense is significant, especially when compared to the cost-effectiveness of traditional reusable instruments, which require strict sterilization protocols, do not necessitate frequent replacement [56].

These instruments, with capabilities that exceed the range of motion of the human hand, facilitate complex procedures such as prostatectomies and nephrectomies with enhanced precision. This ability allows surgeons to execute precise maneuvers that minimize tissue trauma and optimize patient outcomes. Thus, while robotic surgery offers exceptional performance, the financial considerations associated with its implementation remain a critical concern in the discourse on the future of minimally invasive surgical techniques [57].

Innovations and instrumental improvements in minimally invasive urological surgery

Laparoscopy

Laparoscopic surgery is experiencing a transformative phase driven by significant technological advances. The introduction of three-dimensional visualization systems has revolutionized the operative field view, providing surgeons with depth perception that mirrors natural sight, thereby enhancing the accuracy of intricate surgical tasks. These advances have reduced operative times and potentially the rate of perioperative complications [25].

Further innovation includes articulating instruments that offer movement mimicking the human wrist. This leap forward allows for more natural and precise movements within the patient's body, enhancing procedures that require complex manipulations like suturing and delicate tissue dissection, which were once limited to open or robotic surgery [26].

Augmented reality (AR) integration into laparoscopic platforms is an emerging trend, enhancing surgical safety and efficiency. By overlaying vital patient-specific anatomical information onto the real-time surgical view, AR allows surgeons to navigate more accurately and reduces the risk of inadvertent injury to surrounding structures [58].

The Magnetic-Assisted Robotic Surgery (MARS) system represents a significant advancement. Developed by Levita Magnetics, this system utilizes magnetic robotic arms controlled externally along with a conventional laparoscopic camera, enhancing operative efficiency and precision without additional incisions or a surgical assistant. The system has shown promising results in renal and adrenal surgery, with a notably short learning curve [59].

Table 1. Comparison between laparoscopy and robotic-assisted surgery.

Aspect	Laparoscopy	Robotic-Assisted Surgery
Surgical precision	High precision, though slightly less than robotic systems	Superior precision and control, especially in complex tasks
Operative time	Comparable to robotic, depends on the procedure	Can be longer due to the learning curve; improves with experience
Cost-effectiveness	More cost-effective due to lower equipment and training costs	High initial costs for equipment, maintenance, and training
Accessibility	More widely accessible, especially in resource-limited settings	Limited by high costs, affecting widespread adoption
Technological advances	Continuous innovations like 3D visualization and articulating instruments	Advanced features like augmented reality and single-port technology
Training and learning curve	Shorter learning curve with established training pathways	Steeper learning curve but offers potential for faster proficiency in complex procedures
Economic viability	Preferred in settings with financial constraints	High costs pose challenges, especially in lower-income regions
Patient outcomes	Effective with slightly less precision compared to robotic systems	Potential for improved outcomes due to high precision and control

Robotic Surgery

Robotic surgery remains at the forefront of minimally invasive techniques, with recent enhancements like augmented reality significantly advancing the field. AR in robotic platforms enables surgeons to operate with an enhanced real-time view of the patient's anatomy, facilitating precise tissue dissection, organ sparing, and accurate pathology identification [60].

Developments such as Single Port (SP) technology simplify complex procedures by allowing all surgical instruments to pass through a single incision, reducing surgery invasiveness and potentially easing postoperative pain and recovery time [61].

The evolution of the da Vinci platform continues to influence the field significantly. Its latest iteration offers improved control and expanded capabilities, featuring advanced articulation, tremor filtration, and superior ergonomics, designed to facilitate complex surgical tasks with unprecedented precision [62].

Collectively, these developments in laparoscopy and robotic surgery are shaping a future where enhanced vision, greater precision, and advanced instrumentation redefine the possibilities of minimally invasive surgery. These technologies are set to deliver increasingly successful surgical outcomes, emphasizing patient-specific, tailored interventions that minimize disruption of bodily functions and accelerate postoperative recovery. These advances promise to bridge the gap between traditional methods and the precision of modern robotics, democratizing access to high-quality minimally invasive surgical care (Table 1).

Conclusions

The comparative analysis of laparoscopic and robotic-assisted surgical techniques in urology provides detailed insights into their respective roles, efficiencies, and challenges. Laparoscopy continues to anchor minimally invasive surgical practice, proving to be both effective and cost-efficient, especially in resource-limited settings. Although robotic surgery offers advanced capabilities, its high costs limits widespread adoption. Enhancing laparoscopic training is crucial in financially constrained regions to maintain high quality surgical care. Laparoscopy's ongoing technological advancements ensure that it remains a robust alternative to robotic surgery, maintaining accessibility and efficacy. This study highlights the need to balance technological advances with economic and accessibility constraints, ensuring the benefits of minimally invasive surgery reach all patient demographics, optimizing outcomes across diverse clinical landscapes.

Declarations

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