Robotic-Assisted Systems in Gynecology: A Systematic Review

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***Abstract*- Gynecological surgery involves a range of surgical procedures addressing organs within the female pelvic region, such as the uterus, ovaries, cervix, fallopian tubes, vagina, and vulva. Common procedures include hysterectomy, laparoscopic surgery, fibroid removal, myomectomy, and ovarian cyst removal. This review provides a comprehensive overview of the evolution of robotic surgery in gynecology, specifically focusing on Robotic-assisted surgery (RAS). It also presents a comparative analysis of robotic surgery compared to laparoscopic and open surgery. The study explores various devices and platforms utilized in robotic surgery, emphasizing the assessment of operative times, surgical outcomes, and challenges associated with different techniques. Research findings suggest that robotic surgery generally results in shorter post-surgical hospitalization periods than open surgery, with differences that are less distinct compared to laparoscopic surgery. The decision to incorporate robotic surgery into mainstream gynecological procedures is likely to hinge on future advancements and innovations in this field.**

Keywords- Robotic-assisted surgery, da Vinci, VR, master slave, minimal invasive surgery, laparoscopy, degree of freedom.

I. Introduction

Traditional surgical techniques such as laparoscopic and open surgeries have been an integral part of gynecological procedures for the past two decades. However, these methods have limitations, including increased blood loss, longer hospital stays, and a lack of precision. In response to these challenges, robotic surgeries were introduced in gynecology. The introduction of the first surgical robot, PUMA560, in 1985 for performing CT-guided brain biopsies signifying the commencement of a new generation in which robotic systems assisted medical professionals in performing various medical procedures [1]. During the first generation of medical robotics (1990-2000), several robotic systems were developed, including Neuro-Mate, ROBODOC Surgical System, AESOP Robotic Surgical System, CyberKnife System, Zeus Robotic Surgical System, CASPAR, and Da Vinci Surgical System. Among these systems, AESOP, Zeus Robotic Surgical System, Da Vinci Surgical System, and CyberKnife System were utilized to assist in minimally invasive gynecological surgeries, revolutionizing the field. [2]

II. Evolution in Robotic-Assisted Systems

A surgical robot is defined as a computer-controlled powered apparatus that can be programmed to manipulate instruments and perform surgical procedures [3]. With a history spanning over 30 years since their inception, these robots have assumed a pivotal role in the contemporary landscape of surgical practice. The advent of robotic surgery occurred during a time characterized by a growing need for improved surgical accuracy and safety. This development took place in an era where surgeons were increasingly adopting minimally invasive surgical (MIS) technologies to elevate the quality of their results. This article delves into the evolution of robotic surgical systems over the past two decades, commencing with AESOP, the pioneering robot employed for gynecological procedures. [4]

A. AESOP

In 1994, the FDA granted approval for the first surgical robot, AESOP (automatic endoscopic system for optimal positioning; Computer Motion, Inc., Goleta, CA), designed to assist in laparoscopic procedures across general and gynecological surgery. As illustrated in Fig. 1, AESOP, a highly successful semi-active surgical robot, employed a securely attached arm on the operating table's rail to maintain a stable view of the surgical field, preventing fatigue in the endoscope. The robot was designed to be responsive to the surgeon's voice commands and could be manipulated using foot pedals or manual controls to adjust the endoscope's position throughout the course of the surgery [5]. With its widespread adoption, AESOP became one of the most prevalent semi-active surgical robots, with hundreds of units actively deployed in medical settings. [3]. It operated under computer control with read-only memory software. This robotic assistant was capable of performing various procedures, including hysterectomy, adnexectomy, and ovarian cyst enucleation. In the long run, AESOP proved to be a cost-effective solution, serving as a replacement for traditional human assistants and delivering a more stable surgical field to the operating surgeon [6].

Fig. 1. AESOP [9]

B. ZEUS

The ZEUS system was comprised of 2 distinct sides: the "surgeon-side," which featured a console for surgeon involvement, and the "patient-side," encompassing 2 robotic arms responsible for translating the surgeon's instructions into actual instrument manipulation. Additionally, it included an extra robotic arm for controlling the endoscopic camera, which could be directed through voice commands. A wide array of surgical instruments could be attached to the robotic arms, allowing the surgeon to activate graspers, scissors, hooks, and more by operating the controls on the distant console. A more modernized iteration of ZEUS incorporated ergonomic handles and a Storz three-dimensional (3D) imaging system.

This advanced version relied on two isolated right and left video cameras for visualizing the surgical area, a computer for merging as well as accelerating frames from the two cameras, and a video monitor with a responsive medium casing its surface, as depicted in Fig. 2 [7]. The ZEUS surgical system was revolutionary, being one of the initial robotic devices to genuinely explore the concept of tele-surgery, encompassing the capacity to conduct surgical procedures from a remote location. [8].

This innovation optimized the surgeon's intraoperative prowess while introducing a supervised mode for simulation and training purposes, catering especially to non-expert surgeons. The Si robot featured an enhanced imaging system seamlessly integrated with the Tile-Pro software, enabling real-time fluorescence imaging via the Firefly technology. This upgrade played an instrumental role in advancing the system's utility for minimally invasive surgery. Then came the Da Vinci Xi platform, introduced by Intuitive Surgical in 2014, representing one of the most efficient systems to date. The Xi model creatively reimagined the design of the patient cart, enhancing its flexibility and addressing some of the limitations previously encountered with the Si platform. The most recent iteration, the multi-port da Vinci Xi model, has admirably surmounted these limitations encountered in the previous prototype. Furthermore, it has introduced novel technologies that further augment robotic surgery, as elegantly showcased in Fig. 4 [12]. The Da Vinci surgical system has been successfully applied across a spectrum of gynecological procedures, encompassing tubal anastomosis, ovarian transposition, hysterectomy, myomectomy, and vaginal vault prolapse repair [13]. Multiple studies have corroborated its safety, efficacy, and feasibility. However, it is important to note that this platform, while offering substantial benefits, presents a more limited array of instruments and does not incorporate EndoWrist technology.

Fig. 2. ZEUS [10]

C. DA VINCI

The da Vinci system's development stemmed from groundbreaking technological innovations pioneered at the Stanford Research Institute in the United States, ultimately securing FDA approval in the year 2000. Identical to the ZEUS system, the da Vinci system boasted between 3-4 robotic arms. However, in this case, these robotic arms were affixed to a surgical cart placed next to the operating table, an arrangement elucidated in Fig. 3. These highly advanced robotic arms were equipped with instrument tips capable of articulating in multiple planes, akin to the human wrist, thus granting the robotic arm an impressive 7 degrees of freedom. During surgical procedures, the surgeon employed binoculars at the surgical console to immerse themselves in a genuine 3D view of the operation.

The console ingeniously projected images that convincingly simulated the surgeon's hand directly manipulating the instruments within an accessible operative site. A simple press of a foot pedal translated the surgeon's hand actions into seamless management over the robotic arm responsible for camera [11]. Subsequent to the initial prototype, Intuitive Surgical introduced the da Vinci S in 2006, marking a significant leap forward. This updated platform featured a 3D high-definition (HD) camera system, accompanied by a streamlined setup that incorporated an interactive touchscreen display. In 2009, the da Vinci Si model was introduced, revolutionizing surgical capabilities with the concept of dual Console surgery.

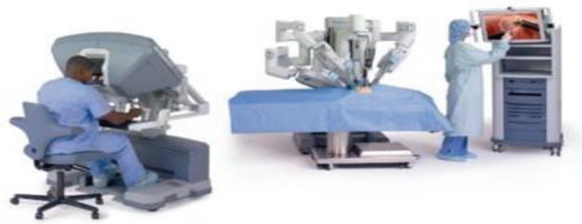

Fig. 3. DA VINCI [14]

Fig. 4. DA VINCI Si (Left) and DA VINCI Xi (Right) [15]

D. LESS

In 2009, Fader and Escobar were the first to report on the utilization of Laparoendoscopic Single-Site Surgery (LESS) in gynecology. LESS is a small incision surgical technique that involves creating a single small incision in the abdominal region, typically near the umbilicus. This approach employs a specialized device, known as a single-port, or a grouping of several small incisions in one location, through which laparoscopic trocars are inserted. This innovative approach presents certain challenges, including difficulties in maintaining proper camera orientation and the necessity for synchronized movements of both the camera and surgical instruments, demanding a high level of precision. Nevertheless, LESS procedures are often more cost-effective and are considered advanced laparoscopic techniques [16].

E. SPORT

Titan Medical, headquartered in Toronto, Canada, pioneered the development of SPORT (Single Port Orifice Robotic Technology), an innovative robotic surgical equipments that offered a more compact and less cumbersome alternative to the da Vinci system. SPORT featured a surgeon remote workstation and a robotic arm, making it a promising addition to the field of small incision surgery. The foundation of this system stemmed from IREP technology, which Titan Medical licensed from Columbia University. Notably, SPORT was distinguished by its 25-mm single access port, housing two snake-like operating instruments with a diameter of 6 mm, alongside a cutting-edge 3D-HD camera, as depicted in Fig. 8. Initially, SPORT set its sights on applications in gynecology, general surgery, and urology procedures.

This system was designed to facilitate LESS (Laparoendoscopic Single-Site Surgery) procedures as well as boasted a range of advanced features, including a high-resolution camera, an intuitive haptic interface, and a sophisticated visual tracking system [17].

F. SENHANCE and REVO-I

Numerous systems, such as SPORT by Titan Medical and Surgibot by Transenterix, aimed to replace the Da Vinci system. Unfortunately, these systems faced challenges in obtaining official authorization and developing products suitable for enhancing surgeons' minimal access techniques. However, two products did manage to secure regulatory approval in certain countries for regular clinical use: the Senhance Surgical Robotic System and the REVO I Robotic Surgical System [18].

1) Senhance Surgical Robotic System (Transenterix, USA)

The Senhance Surgical Robotic System, initially known as ALF-X, originated from the Italian company Sofar. The introduction of robotic surgery using the Senhance system occurred at Klaipeda University Hospital in Lithuania on November 19, 2018, where a total of 100 operations were performed within the initial 4 months [19]. This system consisted of various components, including a remote-control unit known as the cockpit, a 3D HD Monitor, an infrared Eye Tracking system, a foot pedal, a keyboard, and a touchpad. It set itself apart by featuring up to 4 individual robotic arms, differentiating it from the Da Vinci's four-armed operation cart. The system also had a connection node and sustainable laparoscopic instruments, as illustrated in Fig. 6. The Senhance system had the flexibility to be compatible with any 3D optics system. Notably, its eye tracking system enabled camera control by inspecting different components of the surgical field, and the instrument handles provided haptic feedback, assisting in tasks like suturing and dissection. Surgeons utilised fully flexible seats, and the vertical stance which allowed others in the room to observe the same system as the surgeon. For access, a 10 mm trocar was needed. The use of reusable laparoscopic instruments brought a significant cost benefit when compared to the Da Vinci device.

Fig. 5. SENHANCE[21]

2) REVO-I Robotic Surgical System

The REVO I Robotic Surgical System underwent clinical testing after receiving approval from the Korean Food and Drug Administration (FDA) in 2017.

As illustrated in Fig. 7, the REVO I system comprised a master surgeon control console (MSRC-5000), a slave 4-arm robotic operation cart supervised mode for simulation and training purposes, catering especially to non-expert surgeons.

(MSRO-5000), and a sharp clarity vision cart (MSRV-5000). All instruments were planned for reusability, with usage monitored. Notably, the REVO I system featured compact instruments than the Da Vinci-Xi™ surgical system [20]. Porcine studies demonstrated a reduction in the learning curve and the system's safety during usage. It was reported to have been employed in procedures such as fallopian tube reconstruction, partial nephrectomy, and cholecystectomy, as well as in porcine models. The instruments were sustainable up to 20 times, in contrast to the Da Vinci instruments, which were limited to 10 uses, effectively reducing equipment costs [18].

Fig. 6. REVO-I [22]

G. VERSIUS

In 2019, CMR Surgical, known as Cambridge Medical Robotics, introduced its Versius robotic surgical system. This system featured a series of autonomous arms, each with its own base. These arms were designed to be compact, lightweight, and easily movable around the surgical table as required. Furthermore, the arms were constructed to resemble the human arm, with three joints that replicated the actions of the human shoulder, elbow, and arm. The system provided a 3D view, as depicted in Fig. 11.CMR Surgical offered various flexible payment models for acquiring Versius, ranging from the conventional initial capital acquisition to a controlled service model. The latter included the robot, all necessary instrumentation, and management in a yearly contract based on agreed-upon technique capacities, with the aim of reducing the overall duration cost of robotic surgery. CMR achieved a significant milestone when it completed the first sale of the Versius system in India to the Galaxy Care Hospital in Pune. This marked the hospital as the world's first to acquire the Versius surgical robotic system [23].

H. MANTRA

India is poised to introduce its first domestically developed and cost-effective general robotic surgical system, known as the Multi-Arm Novel Telerobotic Assistance (Mantra), created by Dr. Sudhir P. Shrivastava at the Rajiv Gandhi Cancer Institute. This groundbreaking system is anticipated to enter the market by March 2023.The Mantra system features surgical arms that emerge from mobile platforms, providing the flexibility to position them as required around the operating table, ensuring adaptability. Depending on the surgical procedure's requirements, a single process can involve the use of three to five arms.

Notably, a part of these arms is provided with a 3D camera that can be magnified for the surgeon's benefit, as illustrated in Fig 8. Additionally, a touchscreen display is available, allowing the surgeon to access case-related information and other relevant data. In the operating theatre, multiple displays can be set up for other medical professionals, and everyone in the room can use polarized glasses to view the procedure in 3D. The Mantra system has been intelligently designed to address the cost issues associated with existing robotic platforms, which are approximately three times more expensive to maintain [24].

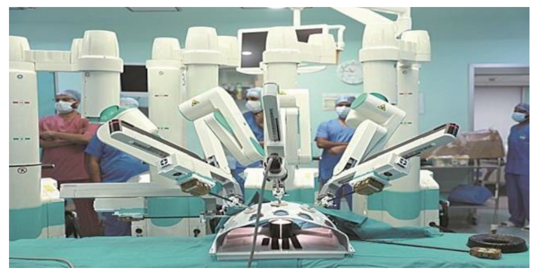

Fig. 7. MANTRA [25]

III. Discussion

Robotic surgery led to a reduction in the number of employees needed in the surgical site, allowing for greater spacing among staff members. Consequently, this helped mitigate the potential of viral transmission to healthcare personnel [28]. These instances highlight that while the adoption of robotics in gynecology is still relatively nascent, it holds substantial potential [29].

TABLE I. Comparison among Open, Laparoscopic And Robotic Surgeries

Parameter	Open	Laparoscopic	Robotic
Description	In this procedure the surgeon directly visualizes the surgical field and uses his/her hands and short Instruments to perform the procedure directly inside the abdomen.	This procedure always involves a thin camera (about the size of a Bic pen) called a laparoscope that is used to visualize the inside of whatever body cavity is being operated on.	In this procedure the surgeon controls every movement of the robotic arms while comfortably seated in a control station next to the operating table. The advanced, three- dimensional camera used by the robotic system offers an immersive experience for incredible visualization of the abdomen.
Size of incision	Large incision depending on the type of procedure performed.	Only three or four small incisions	Similar to laparoscopic
Level of dexterity	The human wrist is less flexible as compared to the robotic. Therefore, less level of dexterity.	Limited range of motion as compared to robotic	Highest as robotic instruments can rotate 360 degrees and are more flexible than a human hand or wrist.

Parameter	Open	Laparoscopic	Robotic
Recovery time	Recovery time is more. Therefore, longer hospital stays.	Less recovery time as compared to open. Thus, shorter hospital stays.	Same as the laparoscopic.
Risk of infection and blood loss	High	Low	Rare
Merits	Despite it being outdated it is still a relevant option in certain cases. For example, when performing an abdominal procedure laparoscopically, it sometimes needs to be converted to an open procedure for patient safety or if there is significant scar tissue in the surgical field. Hence, very complex surgeries may call for an open approach.	Here most patients will experience less pain, a quicker return to work and normal activity, a shorter hospital stay and a shorter overall recovery.	Three-dimensional camera used by the robotic system offers an immersive experience for incredible visualization of the abdomen. Being that the surgeon is seated, the fatigue associated with laparoscopic and open surgery is significantly reduced, giving both the patient and surgeon a better experience.
Cost	Least expensive	Less expensive as compared to RAS	Most expensive

IV. Future Scope

In the 21st century, robotic surgery has seen widespread adoption in medical practice. The FDA has granted approval for the use of robotically-assisted surgical (RAS) devices in controlled operating room settings, enabling trained physicians to perform laparoscopic procedures across various surgical disciplines, including general surgery, cardiac surgery, colorectal surgery, gynecologic surgery, head and neck surgery, thoracic surgery, and urologic surgery [26]. Looking towards the future, advancements in robotics will primarily focus on developing stronger resilient haptic technology to provide further miniaturization of robotic systems, enhanced visual feedback with increased elaboration and amplification, and the advancement of independent robotic systems. Therefore, robotic surgery will be available for delicate treatments like breast cancer (abnormal growth of breast cells in the women's milk duct), colon cancer and lung cancer [31-35]. A futuristic possibility includes microbots, which could eliminate the need for surgical incisions. These microbots could be introduced into the bloodstream and guided to specific target locations, representing the next frontier in minimally invasive surgery. One promising concept is to employ 'capsule robots,' highly miniaturized endoscopic devices applicable in diagnostics, surgical procedures, and drug delivery. These devices can be manipulated using magnetic interactions, offering a tetherless design with exceptional freedom of movement. Due to their extremely small size, they cause minimal tissue damage and provide rapid access to challenging anatomical regions.

Capsule robots have the potential to reach narrow anatomical regions, deliver drugs to specific lesions, and collect valuable data. Despite the fact that robotic surgical systems have been in use for more than two decades, they are still considered to be in their early stages of development. The future holds the promise of unlocking their full potential, introducing new applications, and establishing current practices as standard procedures in healthcare [27]. The utilization of intricate algorithms on high-speed computer networks processes extensive clinical, medical, and biological patient data, leading to the creation of mathematical models. These models hold the promise of addressing challenges in diagnosing conditions, tailoring treatment plans for individuals, and ultimately enhancing patient outcomes. In the realm of clinical gynecology, virtual AI employs pattern recognition to assist in diagnosing gynecological malignancies, planning treatments, and predicting outcomes in areas such as assisted reproductive techniques and urogynecology. In gynecological surgery, physical AI integrates augmented reality into operations through computer-aided or robotic platforms. Despite these advancements, the full integration of AI into modern medical practices for the improvement of patient outcomes in clinical gynecology is still a work in progress [30].

V. Conclusion

A variety of devices and platforms designed for robotic surgery in gynecology have been subject to review. These include AESOP, ZEUS, DA VINCI, LESS, FREEHAND, SPORT, SEHANCE, REVO-I, VERSIUS, HUGO, and MANTRA. Among these, the most widely adopted robotic platform for surgical procedures to date is the da Vinci surgical platform.

In India, the cost of robotic surgeries remains high, leading to hesitancy among individuals to embrace them. However, the emergence of new technologies like MANTRA has the potential to address this issue, paving the way for further advancements in the field of robotic surgery. Consequently, it can be concluded that there is a growing demand for robotic surgery, and on-going efforts are being made to develop and improve these technologies.

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