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Robotic-assisted varicocelectomy: A comprehensive literature review of outcomes, challenges, and future directions

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Abstract

Introduction: Varicocele is the dilatation of spermatic veins within the spermatic cord and is a common condition that arises during puberty. Varicoceles can lead to venous incompetence or absent valves, potentially causing further testicular enlargement. It is a common condition that can impact male infertility. Traditionally, it has been managed through microsurgical or laparoscopic varicocelectomy. Robotic-Assisted Varicocelectomy (RAV) has recently gained attention as an advanced surgical approach for the treatment of varicoceles.

Objective: This review aims to analyze the advantages, limitations, and clinical outcomes of robotic-assisted varicocelectomy based on the literature. It compares it with conventional and laparoscopic surgical techniques and also highlights areas for future research and advancement.

Methods: A systematic review of the literature was conducted to evaluate RAV in terms of operative time, intraoperative and postoperative complications, rate of recurrences, and cost-effectiveness. Data were collected from meta-analyses, systematic reviews, RCTs, clinical trials, and publications from 2014 to 2024.

Results: The findings suggest that RAV offers significant benefits, including improved surgical precision, shorter hospital stays, reduced intraoperative and postoperative pain, and lower recurrence rates. However, the higher cost of robotic systems, the absence of haptic feedback, and the lack of standardized surgical guidelines limit its use.

Conclusion: Robotic-assisted varicocelectomy has potential benefits over traditional techniques. Future research should focus on improving cost efficiency, integrating haptic feedback, and conducting large-scale studies to establish long-term outcomes and standardized guidelines for its use.

Introduction

A varicocele is defined as a result of the dilatation of spermatic veins within the spermatic cord, resulting in a distended meshwork of blood vessels in the scrotum [1]. Particularly, the pampiniform venous plexus enlarges in the scrotum, with approximately 90% of varicoceles being left-sided [2,3]. The formation of varicoceles has been attributed mainly to anatomic variance, increased left renal vein pressure, and incompetent or absent valves [3]. The condition was found to impact semen quality, which has been reported to decline [1]. Moreover, reflux of adrenal metabolites, increased testicular hypoxia, and increased testicular temperature are mechanistic causes that have been proposed [2]. The literature reports an association between varicoceles in adult men and age. Prevalence was found to increase with age, suggesting varicocele development at puberty age, and that venous incompetence occurs during the subsequent testicular development [2].

Typically, varicoceles are asymptomatic and detected incidentally during routine examination. Patients report an uncomfortable feeling in the scrotum, which can affect their quality of life and daily activities [4]. In addition, the condition may compromise

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testicular growth and impact fertility [3]. Varicoceles are divided into a subclinical form that is discovered on ultrasound and a clinical form that can be examined by checking the scrotum. The latter is further subdivided into three grades: Grade 1: palpable during Valsalva maneuver; Grade 2: non-visible but palpable during regular examination; Grade 3: readily visible [4].

Varicocelectomy is considered the most surgically correctable finding in the evaluation of male infertility, accounting for 8-16.2% of the normal male population and 21-39% of infertile men [1]. The indications to perform a varicocelectomy include: (1) infertility; (2) hypogonadism; (3) scrotal pain; (4) pediatric testicular hypertrophy; (5) aesthetic issues with large varicoceles [5].

The literature highlights the benefits of varicocelectomy regarding semen parameters. Multiple approaches exist for the surgical management of this condition, including laparoscopic ligation of spermatic veins, open inguinal approach, retroperitoneal high ligation technique, subinguinal microscopic procedure, and, recently, robot-assisted varicocele repair [1]. These techniques focus on the efficacy of the treatment, reflecting on the reproductive outcomes through assisted reproductive technologies [5]. Nowadays, robotic surgery provides increased dexterity that the operator has with the use of the instruments, improved surgeon ergonomics, and decreased hospital stay time. Furthermore, advanced viewing capabilities, 3-D immersive imaging, and precise movements for complex tasks [1].

Undoubtedly, with time, as surgical robots become more prevalent, accessible, and affordable, surgeons will continue to gain experience, adding to their learning curve, and robot-assisted varicocelectomy will find its place among the top management options for varicoceles [5].

This review aims to evaluate the existing literature regarding robotic varicocelectomy, focusing on surgical approach, clinical outcomes, and cost-effectiveness in clinical practice. By summarizing the latest evidence, we aim to provide a comprehensive overview of the benefits and limitations of robot-assisted varicocele repair and identify areas for future research.

Surgical approach to varicocele repair

Open surgery

For an open varicocelectomy, there are different approaches; the Palomo technique or the subinguinal approach can be used. The Palomo technique is a retroperitoneal technique where a horizontal incision is made at the inferomedial level of the ipsilateral anterior superior iliac spine in a medial direction, then an incision is made in the external oblique fascia following the direction of the fibers and the internal oblique muscle is retracted cranially to visualize the internal spermatic veins proximal to the internal inguinal ring [6]. The exact duration of open Palomo varicocele surgery is not explicitly stated in the available references. However, these sources do discuss various varicocelectomy techniques, including laparoscopic and microscopic approaches, which generally have shorter operative times compared to traditional open surgery. For example, laparoscopic Palomo varicocelectomy has been reported to have an average operative time of approximately 34.2 minutes [7].

The subinguinal approach is based on a transverse 3-cm incision over the external inguinal ring extending to the Scarpa fascia, which is dissected using the index finger. The spermatic cord structures are grasped with a Babcock clamp and stabilized with an army-navy retractor or a Penrose drain. Using a surgical microscope, the external spermatic fascia is incised, and all veins within the spermatic cord are ligated using 4-0 sutures [8]. The reported operative time for varicocelectomy performed via an open subinguinal approach is approximately 35.6±13.5 minutes [9].

Laparoscopic varicocelectomy

A laparoscopic varicocelectomy usually involves three transperitoneal ports. By using either the Hassan or Veress-needle technique, a 5-mm laparoscopic port is positioned near the umbilicus and placed in the peritoneal space. Then, guided by direct vision, two additional 5-mm ports are inserted: one located between the umbilicus and the pubic symphysis, and another positioned lateral to the left epigastric vessels. An incision is made through the peritoneum approximately 3 cm above the internal inguinal ring, overlying the spermatic vessels. The separation of the spermatic vessels from the adjacent tissues is made with the aid of a laparoscopic Doppler. Depending on the surgeon's decision, the testicular artery may or may not be preserved. At the end of the procedure, clips are used for the ligation and division of the veins, the port sites are usually closed with the use of an interrupted absorbable suture, and the skin is closed with the use of a subcuticular suture [10]. The duration of this surgery is approximately 20 to 80 minutes per side [5].

Robot-assisted varicocelectomy (RAV)

Robot-assisted varicocelectomy involves the use of robotic systems to perform varicocelectomy procedures, such as the Palomo technique, enhancing precision and control during spermatic vessel ligation. This approach often integrates advanced technologies like indocyanine green fluorescence to preserve lymphatic structures [11]. The robot is usually positioned on the patient's right side [12]. The procedure requires four ports: three 8-mm robotic ports and one 5-mm assistant laparoscopic port. While the surgical steps are identical in both laparoscopic and robotic-assisted varicocelectomy, the primary distinction lies in vessel ligation, which is performed using clips in laparoscopic varicocelectomy and ligatures in the robotic-assisted technique. The duration of surgery is notably longer for robotic-assisted varicocelectomy compared to laparoscopic varicocelectomy. However, it is important to take into account that the total operative time for the robotic-assisted procedure also includes the docking process, which varies between 10 and 20 minutes depending on the experience of the surgical team [11].

Robot-assisted microsurgical varicocelectomy

In a robot-assisted varicocelectomy, the robot is positioned on the patient's right side, who will be in the supine position, and it is configured for the microsurgical portion of the procedure. The instruments are loaded in the trocars, and for a better range of motion, the instruments are loaded 4-5 cm beyond the tip of the trocar. On the right arm of the robot are mounted the black diamond micro forceps, on the left arm are mounted the micro bipolar forceps, and on the fourth arm are mounted the curved monopolar scissors. Subsequently, a 1-2 cm subinguinal incision is

made above the external inguinal ring. To ensure a good exposure of the spermatic cord, a tongue depressor is used, and then an incision in the anterior cremasteric sheet is made to expose the cord structures. Real-time micro-Doppler can be used to identify the arteries, while all the dilated veins are located, isolated, and ligated with 3-0 silk suture, with the optional use of a Vein Mapper for better identification. To assist in identifying the veins, a Vein Mapper may also be used. The vessels are cut using the curved monopolar scissors, and then the depressor is removed, the cord is repositioned, and the incision, deep tissue, and skin are closed [12]. For the real-time micro-Doppler, there are available the Vascular Technology Inc Micro-Doppler probe and the Hitachi Aloka micro-Doppler probe; the first one produces audible signals while the second one gives a visual image [13]. This surgery typically takes 25 to 60 minutes per side [5].

Clinical outcomes and comparative studies

Success rates and recurrence rates

Recurrence rates in robotic-assisted varicocelectomy vary depending on the surgical technique employed for comparison, as well as specific study methodologies and patient characteristics. Methodological variations, including how recurrence is defined, further contribute to the heterogeneity of reported rates. These factors might underscore the complexity of evaluating recurrence and emphasize the necessity for standardized assessment criteria in future studies.

In addition, a retrospective comparative study of medical records from 40 patients, comparing robotic-assisted versus conventional laparoscopic varicocelectomy, reported no recurrence rate in either case over a 2-year postoperative period [11,14]. Another analysis conducted with pediatric patients observed that robotic-assisted laparoscopic varicocelectomy also had no recurrences, while laparoscopic surgeries resulted in recurrence in 3 out of 8 patients with hydrocele [15].

Open surgical techniques, including subinguinal and retroperitoneal (Palomo) varicocelectomy, continue to be widely employed approaches. Microsurgical subinguinal varicocelectomy, often regarded as the gold standard, offers superior visualization of spermatic vessels and lymphatic preservation, resulting in reduced recurrence and complication rates. However, it demands technical proficiency and microsurgical expertise. Conversely, the Palomo technique, performed at a higher retroperitoneal level, is less technically demanding and expedient but carries a higher risk of lymphatic disruption, potentially leading to hydrocele formation [6,7].

On the other hand, a review of 140 patients who underwent robotic-assisted microscopic varicocelectomy revealed a recurrence rate of 9.6%. This rate is higher than previously reported recurrence rates for microsurgical subinguinal varicocelectomy, which range from 0.82% to 3% in this specific study. The article defined recurrence as any measurable retrograde venous flow. Since the study included only patients with documented venous reflux before surgery, this strict criterion may have contributed to a higher observed recurrence rate compared to previous studies [16].

Complications

Furthermore, analyses of the utilization of robotic assistance in microsurgical procedures, including varicocelectomy, have demonstrated a low incidence of postoperative complications. Among the cases of robotic varicocelectomy, one patient experienced varicocele recurrence, which was confirmed through both physical examination and ultrasound. Additionally, one patient developed a small postoperative hydrocele, while two patients had minor scrotal hematomas, all of which were managed conservatively without surgical intervention. It is noteworthy that this study examined robotic microsurgeries performed in the early 2000s, introducing a temporal bias that may restrict the applicability of its findings to contemporary robotic techniques, which have since undergone advancements in precision and efficiency [17].

A retrospective comparative analysis conducted at a pediatric medical center in Seattle revealed no intraoperative or postoperative complications associated with robot-assisted procedures. The study involved four patients who underwent robotic-assisted laparoscopic varicocelectomy, each paired with two age-matched patients who underwent conventional laparoscopic varicocelectomy. Notably, three of the non-robotic surgery patients experienced persistent pain, while two developed symptomatic recurrence, including hydroceles. All procedures were performed by the same surgeon with a resident or fellow assisting. Statistical comparisons between the groups were conducted using the student t-test and Fisher exact test, with significance set at $P<0.05$ [15].

In contrast to a previous study that identified a risk of postoperative complications associated with traditional microsurgical varicocelectomy [15], another study suggests that robotic-assisted microsurgical varicocelectomy may offer a potential advantage in minimizing these complications [16]. The robotic approach, characterized by enhanced precision, might contribute to a reduced incidence of adverse outcomes, likely due to its ability to provide greater control and improved visualization during surgery. The authors report a complication rate of 3.5% (9 complications out of 258 procedures), with 2.7% (7 complications) being hematomas and 0.8% (2 complications) hydroceles [16].

Recovery time

Furthermore, robotic-assisted microsurgical varicocelectomy is associated with a shorter recovery time. In contrast, patients who underwent traditional microsurgical varicocelectomy typically reported mild to moderate pain for several days post-surgery [16]. Conversely, those who underwent robotic surgery experienced significantly reduced pain and a faster return to normal activities, as evidenced in Table 1.

Comparison with microsurgical and laparoscopic approaches

An article has highlighted the advantages of the robotic approach over conventional laparoscopic techniques. These advantages include three-dimensional optics that facilitate more precise dissection, enhanced stability of movements, and ergonomic instrument design [5]. Another study has corroborated these findings, demonstrating that robot-assisted surgeries effectively eliminate surgeon tremor [17].

Table 1: Comparison of operative times for different varicocelectomy procedures.

Procedure	Study	Operative time (min)	Overall procedure duration (min)
Robot-Assisted (RALV)	Hidalgo-Timola (2009)	112±9.8	38
Robot-Assisted (RMV) – unilateral	McCullough (2018)	57±16	39±9 (docking)
Robot-Assisted (RAV) – unilateral	Parekattil & Cohen (2011)	30(10–80)	N/A
Robot-Assisted Subinguinal	Shu (2008)	71.1±21.1	N/A
Laparoscopic (LV)	Hidalgo-Timola (2009)	73±25	36
Microsurgical (TMV) – unilateral	McCullough (2018)	49±13	N/A
Microsurgical Inguinal	Shu (2008)	73.9±12.2	N/A

Robotic-assisted varicocelectomy can be further categorized into robotic-assisted microsurgical varicocelectomy and robotic-assisted laparoscopic varicocelectomy. Each of these approaches offers distinct advantages and limitations.

The robotic-assisted microsurgical technique combines the precision of robotic technology with the meticulous dissection capabilities of microsurgery. It enables superior visualization and preservation of lymphatic and arterial structures, potentially reducing the risks of recurrence and hydrocele formation. However, it is more time-consuming and costly compared to other approaches [16].

On the other hand, the robotic-assisted laparoscopic procedure integrates robotic assistance with the standard laparoscopic approach, providing enhanced dexterity and visualization compared to conventional laparoscopy. It is generally faster than the microsurgical approach but may not offer the same level of vascular and lymphatic precision [18,19].

The financial implications of various surgical technologies are crucial, as the cost of each procedure varies significantly. Esposito et al. (2024) reported this finding in their study, demonstrating that the total cost of the laparoscopic procedure was 1.587,07 euros (€) compared to 5.650,31 euros (€) for the robotic-assisted procedure (p=0.001) [14]. Furthermore, Hidalgo-Tamola et al. (2009) also conducted an analysis of the financial implications of robotic surgery, revealing that it incurs approximately double the cost compared to conventional laparoscopic procedures (15.800 US dollars vs 8.600 US dollars) [15].

Cost effectiveness and accessibility

Robot-assisted varicocelectomy is being considered as a possible alternative to conventional surgical techniques for the treatment of varicoceles, such as open and laparoscopic varicocele repair. It provides the added advantage of use, such as greater precision and 3-D visualization, among other factors, such as reduced hospital stay (20). Currently, several urological interventions are done through robotic surgery, including varicocelectomy, vasectomy reversal, testicular sperm extraction, and spermatic cord denervation. Although Robot-assisted varicocelectomy has a lot of advantages, like enhanced dexterity and 3D visualization, the factors of high expense and the need for specialized apparatus undermine its broad usage [28]. Currently, several urological interventions are done through robotic surgery, including varicocelectomy, vasectomy reversal, testicular sperm extraction, and spermatic cord denervation. Although Robot-assisted varicocelectomy has a lot of advantages, like enhanced dexterity and 3D visualization, the factors of high expense and the need for specialized apparatus undermine its broad usage [28].

However, the cost-effectiveness of robotic varicocele repair has remained a significant concern. A comparative study by Espacito C Et.al has found that the overall cost for laparoscopic varicocelectomy was €1,587.07, while RAV was €5,650.31, with the laparoscopic technique also having shorter operation time and better cosmetic outcomes [18]. Likewise, a pediatric study by Hidalgo-Tamola J Et.al found that the average total hospital charge for RAV was $15,800, which was considerably more than the $8,600 for LV, and had longer operative times in the RAV group (112 minutes vs. 73 minutes; P=0.02) [19].

The da Vinci Surgical System is a well-known, robotic module that plays a major role in surgery, with a purchase cost of approximately $1.5 million, with the added yearly maintenance costs of $100,000 to $170,000, and instrument costs per procedure further add a significant financial burden to these procedures [21].

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Two main factors should be considered to evaluate the cost-effectiveness of robotic surgery, including the capital equipment cost and the clinical benefits of the procedure [35]. The clinical outcome of robotic surgery is influenced by several factors, including the surgeon's experience and skill levels [35]. A study showed that having an experienced surgeon in robotic surgery can decrease operating time, thus requiring a smaller OR team and potentially reducing the cost of the procedure [35].

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In terms of insurance and healthcare factors, the inclusion of robotic systems in surgery presents challenges in managing risk and covering insurance. Robotic surgeries have high expenses, and thus, healthcare providers and insurers need to scrutinize closely in order to approve coverage policies [23]. Furthermore, the hospital's payment for utilizing their robotic system is strongly related to the type of health insurance and the health care itself. While this is an advantage to nations without universal health care, it remains a major drawback for countries with universal health care [23]. Although there are many benefits in the application of robot-assisted varicocelectomy, the increased cost and handling charges have limited its application in the broader surgical practice, especially in financially disadvantaged settings. There is a lack of research on the influence of insurance coverage on this specific technique, which could be seen as a limitation.

Knowledge gaps

As robotic-assisted varicocelectomy becomes increasingly integrated into clinical practice, it is critical to identify and address existing knowledge gaps to advance the field and ensure optimized patient outcomes. One of them is the lack of standardized surgical guidelines. There has been no single consensus on optimal robotic varicocelectomy technique, differing intraoperative styles, vessel-preserving strategies, and patient inclusion criteria. These variations result in variability in outcomes and highlight the importance of established procedures that can guide surgeons to get reproducible and optimal results [24,25]. The second significant area of gap lies in the absence of large-scale comparative studies.

As robotic-assisted varicocelectomy excels in terms of precision while operating and limiting surgeon fatigue, long-term benefits over conventional microsurgical or laparoscopic techniques remain unestablished. Most of the studies published until now have been with small cohorts or retrospective designs, so establishing firm advantages remains challenging. Without randomized controlled trials for recurrence rates, sperm quality improvements, and outcomes of postoperative pain, it is not yet determined whether robotic-assisted techniques are better or merely comparable to microsurgical varicocelectomy success [26,27]. Furthermore, aside from the need for comparative studies, cost-effectiveness is also a major concern. Robotic-assisted surgery is far more expensive than microsurgical and laparoscopic techniques, and there is actually minimal evidence to justify this increased financial investment. The cost of robotic platforms, along with maintenance and longer operating times, leads one to wonder if the benefits of enhanced visualization and tremor elimination are sufficient to justify the cost. Detailed economic analyses will be central to determining if robotic-assisted varicocelectomy can become a widely available surgical option or if its application must be limited to only highly exceptional cases in which conventional methods are inadequate [28,29].

An additional technological shortcoming of robotic microsurgery is a lack of haptic feedback, an integral component of fine procedures such as varicocelectomy. Unlike traditional microsurgical techniques, where haptic perception supports tissue discrimination and the maintenance of significant structures such as testicular arteries, current robotic platforms only provide visual feedback. This shortage increases the possibility of inadvertent vessel damage and detracts from surgical precision. Addressing this challenge will require the evolution of robotic engineering, for example, the addition of haptic feedback mechanisms to facilitate the surgeon further in performing microsurgical motions with enhanced accuracy [30]. Beyond fertility applications, the role of robotic surgery in the treatment of chronic orchialgia is still uncertain. While robotic-assisted microsurgical spermatic cord denervation (MSCD) has yielded promising pain relief outcomes, long-term comparative outcomes with conventional MSCD are lacking. Also, whether or not robotic techniques provide long-lasting symptom resolution and reduced recurrence rates will be critical to establish in order to extend their clinical application. Further studies should investigate whether robotic-assisted denervation is advantageous in terms of nerve targeting and preservation of tissue, with the possibility of enhanced long-term patient outcomes [31].

Future directions

To address these gaps, future research must prioritize the standardization of robotic-assisted varicocelectomy techniques. Intraoperative protocol development, such as the addition of adjunct imaging modalities like Indocyanine Green (ICG) fluorescence for preservation of lymphatics, can reduce complications such as hydroceles and improve the reproducibility of surgery [11,20,32]. In addition, multicenter large-scale trials are needed to compare long-term fertility results, rates of recurrence, and cost-effectiveness, such that robotic-assisted surgery is held to the same evidence-based standards as all other varicocelectomy techniques [24,33].

Moreover, technological developments in robots will also be crucial in deciding the destiny of microsurgical procedures. Haptic feedback technology may be incorporated to bridge the gap between classic microsurgery and robotic surgery, which increases precision and tissue differentiation [22]. In addition, AI-enhanced surgical navigation will ultimately further augment robotic varicocelectomy by promoting artery-vein discrimination, which improves intraoperative decision-making and refines real-time adjustment to surgical techniques [17,22,34,35]. Furthermore, reducing the price of robotic surgery will also be essential for more widespread use. Examining ways to reduce the cost, such as by enhancing operating room efficiency, designing lower-cost robotic systems, or sharing robotic platforms among institutions, may improve accessibility and make robotic microsurgery a more viable option in more facilities [11,14,28,29,35,36]. Aside from varicocelectomy, future research should also continue to expand the use of robotic microsurgery in pain management and male infertility.

Continued research as to whether robotic-assisted denervation techniques result in reduced recovery times, better pain control, and less recurrence than traditional methods will aid in determining their broader clinical applicability. Ongoing research in the area may yield new applications of robotic microsurgery

beyond fertility preservation, further establishing robotic technology as a component of urologic practice [31,37].

Conclusion

In conclusion, robotic-assisted varicocelectomy showed a lower chance of recurrence compared to conventional laparoscopic varicocelectomy. RAV also demonstrated a low incidence of intraoperative and post-operative complications.

However, significantly higher costs are associated with RAV, and also lack of standardized guidelines leads to variations in outcomes. Furthermore, the absence of large-scale comparative studies creates a significant knowledge gap. Large-scale multicenter randomized controlled trials are necessary to compare long-term fertility outcomes, long-term symptom resolution, recurrence rates, and cost-effectiveness of robotic-assisted varicocelectomy.

Robotic-assisted varicocelectomy holds the potential to become the future standard in microsurgery. Advancing research and technological advancements will be the key to maximizing its precision, accessibility, and impact on patient outcomes.

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