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在线全文

A Review of Robotic vNOTES Surgery: Current Applications, Advantages, and Future Directions

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[**Abstract**] Over the past 500 years, the convergence of three distinct paths – vaginal surgery, laparoscopy, and robotic technologies – has enabled the development of robot-assisted vaginal natural orifice transluminal endoscopic surgery (RA-vNOTES). The ongoing evolution of vaginal surgery has led to contemporary procedures such as hysterectomy, myomectomy, sacrocolpopexy, adnexal interventions, and oncologic operations, applicable to a wide range of diagnoses and pathologies. This approach offers patients significant benefits, including superior cosmetic outcomes, less pain, lower infection rates, and faster recovery of baseline quality of life. Surgeons benefit from improved ergonomics, better visualization, the ability to use multiple instruments, and enhanced tremor control. Robotic assistance has greatly expanded the ability to safely perform more complex cases, such as excision of stage 4 endometriosis with complete posterior cul-de-sac obliteration, as well as other procedures previously considered contraindicated in traditional vaginal surgery. Here, we present current findings and advances in RA-vNOTES and consider future developments in robotic surgery aimed at further improving minimally invasive techniques.

[**Key words**] Robotic surgery vNOTES Gynecology Minimally invasive surgery Surgical innovation Review

机器人辅助经自然孔道内镜手术当前应用、优势及未来发展方向

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【**摘要**】 在过去的500年中，阴道手术、腹腔镜手术与机器人技术三条独立发展的技术路径逐步走向融合，最终催生了机器人辅助经自然孔道内镜手术（robot-assisted vaginal natural orifice transluminal endoscopic surgery, RA-vNOTES）。阴道手术的不断演进，推动了子宫切除、肌瘤剔除、骶骨阴道固定、附件手术及肿瘤手术等现代术式的形成，这些术式现已广泛应用于多种疾病诊断与病理类型。对患者而言，该方法具有显著优势，包括创伤更小、美容效果更佳、术后疼痛更轻、感染率更低，且能更快恢复到术前的健康状态。对医生来说，则可获得更符合人体工学的手术姿势、更清晰的视野、能同时操作多种器械的能力，以及更有效的手部抖动控制。机器人辅助技术大幅拓展了安全实施复杂手术的可能性，例如切除伴有后穹窿完全闭锁的Ⅳ期子宫内膜异位症，以及其他传统阴道手术难以处理的病例。本文介绍RA-vNOTES的最新研究进展，并探讨机器人手术在未来如何进一步优化微创技术。

【**关键词**】 机器人手术 vNOTES 妇科 微创手术 外科创新 综述

The least invasive surgery currently available in gynecology is vaginal natural orifice transluminal endoscopic surgery (vNOTES). Since 1 512, when GIACOMO BERENGARIO first described vaginal hysterectomy, multiple advancements have enabled robot-assisted vNOTES (RA-vNOTES)[1].

The first laparoendoscopic single-site surgery (LESS) was described in 1969 by C. WHEELESS, who performed a laparoscopic bilateral tubal ligation[2]. In 2003, gastroenterology colleagues accessed the peritoneal cavity via a peroral transgastric approach, creating a new entry point and procedure called natural orifice transluminal endoscopic surgery (NOTES). This method continued to evolve, eventually being performed through the vagina – first by gastroenterology, then urology – before C.L. LEE demonstrated the first vaginal NOTES (vNOTES) for gynecologic use[3-6].

Straight instruments with poor triangulation and cumbersome ergonomics made this approach challenging for surgeons. Meanwhile, robotic surgery became more common, and in 2015, C.L. LEE reported the first robot-assisted vNOTES (RA-vNOTES)[7]. Combining robotic technology with the vaginal approach provided significant benefits for both surgeons and patients. For surgeons, the

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robot offered improved ergonomics, enhanced visualization, wristed instrumentation, and tremor-free movements. For patients, RA-vNOTES resulted in shorter surgery times, reduced postoperative pain, and lower rates of superficial surgical site infections[8].

Over the past 10 years, technology has adapted to single-port principles, leading to devices specifically designed to overcome previous limitations. This review highlights the use of RA-vNOTES and the wide range of procedures enabled by the vaginal approach.

1 Methods

The literature search was conducted in PubMed, Medline, and the Cochrane Library using the following keywords: robotic natural orifice transluminal endoscopic surgery, robot-assisted vaginal natural orifice transluminal endoscopic surgery (RA-vNOTES), single-port RA-vNOTES, and single-port robot-assisted natural orifice transluminal endoscopic surgery. The searches were limited to gynecologic surgery, yielding 66 publications in PubMed, 0 in Medline, and 1 in the Cochrane Library.

The search included all studies from each database's inception through July 7, 2025. Inclusion criteria were publications focusing on the gynecologic application of the RA-vNOTES approach. No exclusion criteria were defined. This publication is not a systematic review; the search criteria are outlined to demonstrate the limited number of publications on these keywords.

Descriptions of the technical aspects of the procedures are based primarily on the methodology used by a single fellowship-trained minimally invasive gynecologic surgeon at one academic center. Methodological deviations from these procedural steps are cited as appropriate.

2 Technical overview of robotic vNOTES

For all RA-vNOTES procedures, indocyanine green (ICG) is injected into both ureters before the procedure. In our practice, this approach is chosen because it takes approximately four minutes to place stents and inject ICG before robot docking, compared to the inefficiency of undocking the robot mid-procedure to place stents. As most of our cases involve endometriosis excisions, ICG assists with ureteral identification[9].

2.1 Hysterectomy

After ICG stent placement, the peritoneum is entered in the standard manner for vaginal hysterectomy using the conventional clamp-cut-tie method. This continues until the total hysterectomy is complete or until pelvic pathology prevents safe continuation. At that point, the robot is docked.

Once the peritoneum is entered, regardless of hysterectomy completion, a self-retracting ring is sutured at the 5, 7, 10, and 2 o'clock positions using the 4-P port anchoring technique[10]. The appropriate port is then attached to the ring, and pneumoperitoneum is established. An intra-abdominal and pelvic survey is performed with a laparoscopic camera to ensure there is no endometriosis in the upper abdomen. After confirming that the pathology is confined to the pelvis, the robot is docked. At the end of the procedure, the steps are reversed to close the vaginal cuff.

2.2 Relevant publications

Two direct comparisons have been made between the da Vinci robotic Xi RA-vNOTES and traditional laparoscopic vNOTES (T-vNOTES) for hysterectomy in benign cases. KOYTHONG *et al.* compared RA-vNOTES (n = 35) and T-vNOTES (n = 79), finding similar operative times, estimated blood loss, hospital stays, and pain scores over three weeks[11]. Similarly, ZHANG *et al.* compared RA-vNOTES (n = 8) and T-vNOTES (n = 17), reporting similar safety and feasibility, with no significant differences in operative time, hospital stay, blood loss, or postoperative complications. Notably, ZHANG *et al.* found significantly less pain on postoperative days 1 and 3 in the RA-vNOTES group (n = 8)[12].

Both studies support the safety and feasibility of RA-vNOTES. KOYTHONG *et al.*reported six conversions in the T-vNOTES group and none in the RA-vNOTES group. These six conversions in the T-vNOTES group suggest that the robotic platform may reduce the likelihood of intraoperative complications, especially in patients with challenging pelvic anatomy. Additionally, in the ZHANG *et al.* study, the reduced pain in the RA-vNOTES group may be due to more precise dissection and less tissue trauma with the robotic platform. This finding suggests a potential patient-centered benefit of RA-vNOTES. Table 1 summarizes the main differences between the studies,

Table 1　Comparisons between RA-vNOTES and T-vNOTES

Feature	KOYTHONG *et al*., 2021 (JMIG)	ZHANG *et al*., 2024 (Medicine - Baltimore)
Design	Retrospective cohort study	Case-control study
Setting	Academic tertiary center (USA)	Single hospital (*China*)
Sample size	114 patients total (35 RA-vNOTES, 79 T-vNOTES)	25 patients (8 RA-vNOTES, 17 T-vNOTES)
Surgical platform	Robotic Xi system	da Vinci surgical system (assumed Xi or X)
Primary outcome	Operative time (equivalence)	Surgical outcomes and pain scores
Operative time	No significant difference ($P = 0.37$)	No significant difference
Estimated blood loss	No significant difference ($P = 0.27$)	No significant difference
Pain scores	No significant difference at weeks 1-3	Significantly lower pain scores in RA-vNOTES group on POD 1 and 3 ($P = 0.006$, $P = 0.045$)
Conversions	6 in T-vNOTES vs. 0 in RA-vNOTES (not statistically significant)	0 conversions in either group
Complications	No major complications; all within expected range	1 intraoperative hemorrhage in T-vNOTES, 1 wound issue in RA-vNOTES
Conclusion	RA-vNOTES is feasible and may improve access for robotic surgeons	RA-vNOTES is feasible and may reduce postoperative pain

primarily the increased statistical power from the 114 patients in Koythong's work. However, both studies are single-surgeon, single-center studies, which limits the generalizability of their findings. Neither study evaluates long-term outcomes such as vaginal cuff healing, sexual function, or symptom recurrence, limiting the ability to fully compare surgical efficacy beyond the immediate postoperative period[11-12].

THIGPEN *et al*. conducted a large retrospective study comparing surgical outcomes of RA-vNOTES ($n = 159$) and robotic-assisted single-site port (RSSP) ($n = 269$) in 428 patients who underwent hysterectomy for benign indications by a single surgeon from 2015 to 2022. The RA-vNOTES group had significantly shorter operative times (132 min vs. 146 min, $P = 0.0001$), lower postoperative pain scores at weeks 1 and 3, and fewer superficial surgical site infections (0.6% vs. 4.5%, $P = 0.03$). This study strongly supports the efficacy and enhanced recovery profile of RA-vNOTES compared to RSSP hysterectomy, likely due to intraperitoneal access via a natural orifice[8].

Additionally, the benefits of vNOTES compared to abdominal laparoscopy include decreased postoperative pain, faster recovery, improved cosmesis, shorter operative time, reduced hospital stay, and less estimated blood loss. These advantages were achieved without increasing intraoperative or postoperative complications, readmissions, 24-hour pain scores, or hemoglobin changes between the abdominal laparoscopic and vNOTES hysterectomy groups[13].

Expected patient concerns regarding procedures performed solely through the vagina, such as dyspareunia, pelvic pain, and quality of life, have not been substantiated, as current data do not show significant differences compared to laparoscopy[8, 14].

The vNOTES approach is highly versatile and has been successfully used for hysterectomy, adnexal surgery, myomectomy, sacrocolpopexy, isthmocele repair, and lymphadenectomy[15]. Despite its benefits, vNOTES has limitations. The use of straight laparoscopic instruments in a confined orifice restricts maneuverability and triangulation. This challenge is compounded by the need for at least two surgeons or a surgeon with an appropriate assistant. Many of these limitations are addressed with the assistance of a robotic platform[16].

The da Vinci Xi system was first used for vNOTES in four cases in 2014 by CHYI-LONG LEE. At that time, several limitations were noted, mainly related to instrumentation, and patient selection was considered very important[7]. Ten years later, a case series of 298 patients demonstrated the versatility of RA-vNOTES. The robotic system provided three-dimensional visualization, articulating instruments, reduced surgeon tremor, and decreased surgeon fatigue due to improved ergonomics. The wristed robotic instruments, in particular, facilitated dissection and suturing[17].

Though an improvement, the da Vinci Xi remained a platform based on a multi-port design. In 2014, the United States Food and Drug Administration (FDA) approved the

da Vinci SP (Single Port) robotic platform, with its first use in 2018[18]. The SP was first used for gynecology in 2023, both transumbilically and transvaginally[19]. Colleagues in China also recognized the potential of single-incision surgery, developing the Jingfeng SP1000 and showcasing its performance through the vNOTES approach on 20 patients in 2024[20-21]. In parallel, the Shurui, another Chinese SP platform, was presented at the first Gynecological Minimally Invasive Oncology and Artificial Intelligence Conference. When compared transumbilically, the Shurui had outcomes comparable to the da Vinci robotic platform, but further data regarding the vNOTES approach are limited[22].

While the aforementioned platforms offer similar designs, the Hominis system by Memic Innovative Surgery Ltd. (Yehuda, Israel) was intended to mimic the surgeon's upper extremities. LOWERSTEIN *et al.* described a prospective study on the use of the Hominis system in women undergoing bilateral salpingo-oophorectomy. Although the instruments are placed vaginally, a camera must be placed transumbilically for visualization throughout the surgery[23]. Comparisons of the robotic systems are shown in Table 2.

3 Clinical applications

3.1 Benign gynecologic conditions

3.1.1 Hysterectomy

For vNOTES, the procedure begins with cystoscopy to place ureteral stents and inject ICG. This approach has been shown to save time when there is concern for endometriosis or adhesions[9].

After ICG stent placement, vaginal hysterectomy is initiated in the standard manner with the goal of completing the total hysterectomy. However, when the size of the uterus or adhesions prevents completion of the hysterectomy, the robot must be docked before the procedure can be finished. In these cases, the cervicovaginal junction is scored, and the robotic port is sutured to the vaginal mucosa using the 4-P port anchoring technique[10]. The peritoneal ring is then rolled down to the peritoneum, and the robot is docked. Table 3 outlines the early evolution and application of RA-vNOTES.

Table 3 demonstrates the feasibility of the da Vinci Xi and SP platforms for vNOTES hysterectomy, even in technically challenging cases such as obesity, large uterus, or deep endometriosis. Complication and conversion rates are low in the cited studies. The da Vinci SP provides better ergonomics and instrument articulation, while the da Vinci Xi demonstrates strong adaptability in patients with high BMI. RA-vNOTES with the da Vinci Xi system is ideal for institutions with existing Xi systems, offering benefits such as wristed instruments, versatile docking, and adaptability. The da Vinci SP surpasses the Xi with superior triangulation, reduced instrument clutter, single-arm docking, and shorter docking time. These advantages are especially beneficial in confined vaginal spaces. To optimize the use of the da Vinci Xi and SP platforms, specific training is recommended.

Table 2 Comparison of different vNOTES robotic platforms

Platform	Access configuration	Key features	vNOTES suitability	Strengths	Limitations
da Vinci Xi *(intuitive surgical)*	Multiport	Conventional robotic arms; 8 mm ports	Moderate	Widely available-excellent visualization-wristed instruments	Bulky for vaginal access-requires workarounds (GelPOINT + retroflexion)-not optimized for natural orifice access
da Vinci SP (single port) *(intuitive surgical)*	Single port (25 mm cannula)	3 multijointed instruments + flexible camera-ideal for confined spaces-entry through posterior colpotomy	High	Purpose-built for narrow access-natural fit for vNOTES-minimal collision	Costly-limited availability-no energy devices on some instruments (in early generations)
Shurui SR-01 *(China)*	Single port, multi-arm adaptable	Emerging domestic Chinese system-SP-compatible-instruments allow endowrist-like motion	Emerging potential	Designed for cost-effective robotic MIS-local integration in Chinese hospitals	Limited international experience-lack of published clinical vNOTES trials
Jingfeng (Jingfeng medical technology) *(China)*	Flexible port platform	Robotic SP with optional flexible arms-modular design	Emerging	Designed for hybrid orifices (rectum, vagina)-early flexibility for NOTES	Clinical data limited-needs validation in gynecology
Memic Hominis *(Israel/USA)*	Transvaginal or mixed (camera via umbilicus)	Miniature robotic arms introduced vaginally-camera inserted through umbilicus (hybrid-NOTES)	Hybrid	True NOTES entry for instruments-designed specifically for gynecology-ergonomic and compact	Not true "pure vNOTES"-Umbilical camera limits cosmesis-FDA approval is restricted; still emerging

Table 3　Early evolution and application of RA-vNOTES

Study	Platform	Hysterectomy sample size	Key indication	Mean op time/min	EBL/mL	Conversion	Key findings
GUAN *et al*., 2023	SP	Technique Paper	Hysterectomy	—	—	0	Stepwise RSP-vNOTES protocol ensures safety
GUAN *et al*., 2024	SP	28	CPP, endometriosis	188.7	32.1	1	High feasible with severe endo; excellent visualization
KANNO *et al*., 2025	SP	1	Large uterus (970 g)	102	50	0	SP-VANH is feasible and offers enhanced dexterity in large uteri
LEE *et al*., 2015	Early robot-assisted NOTES	4	Adenomyosis, leiomyoma	198.8	180	0	High docking time; good access, limited by instruments
LIU *et al*., 2023	Xi	1	BMI 70, 16-week uterus	—	—	0	Tailored exposure allows safe hysterectomy in extreme obesity
MEI *et al*., 2023	Xi (Gasless)	14	Hysterectomy	Similar	Minimal	0	GR-vNOTES is comparable to traditional methods; safe, minimal fever
YANG *et al*., 2020	RGPT (rigid wristed via glove port)	13/35	Myoma, cyst, hysterectomy	160	—	0	Parallel setup improves triangulation, no complications
YANG *et al*., 2024	Xi	286/298	Endometriosis, AUB, CPP	138	50	1%	High feasibility even in complex cases; 64% endo resection

3.1.2　Myomectomy

Performing a myomectomy using the RA-vNOTES approach presents challenges distinct from those encountered during a hysterectomy. In some cases, myomectomy can be more difficult because the uterus itself becomes an additional obstacle in the surgical field. Type 6 or type 7 leiomyomas, located mainly on the posterior or anterior aspect of the uterus, allow for easier surgery, as they are accessible through an anterior or posterior colpotomy[24]. However, more complex procedures have also been performed, including myomectomies for type 3-7 leiomyomas[25]. Leiomyomas up to 8 cm in size have been removed via RA-vNOTES[26]. In a case series of 17 patients, myomectomy was performed via laparoscopic vNOTES with the patient in the prone position, allowing removal of leiomyomas weighing up to 519 grams[27]. The various myomectomy techniques are summarized in Table 4.

3.1.3　Procedure

Depending on the location of the leiomyoma, a colpotomy is performed. In our practice, the cervicovaginal junction is infiltrated with dilute vasopressin, and the mucosa is incised with an angled electrosurgery device 5 mm from the cervix. This distance is selected to provide adequate tissue for closing the colpotomy at the end of the procedure. The posterior cul-de-sac is entered with cold Mayo scissors and extended laterally. The apices are sutured with 0-polyglactin suture in a figure-of-eight pattern to prevent lateral extension. The peritoneum is then sutured to the mucosa at the 6 and 12 o'clock positions. A self-retaining ring is placed, serving as a portal to the peritoneum and as a retractor when positioned in the posterior colpotomy to keep the uterus elevated and out of the surgical field. The robot is then docked.

3.1.4　Ovarian cystectomy

Entry for adnexal surgery is performed similarly to peritoneal entry for myomectomy. Typically, a posterior colpotomy is used, as the adnexa are likely to be resting in the posterior cul-de-sac. In addition to the ring retractor used for peritoneal entry, some groups have used a uterine manipulator to elevate the uterus.

Emergent cases have also been performed via vNOTES. A small case series by CHEN in 2020 reviewed 12 patients who underwent management of ectopic pregnancies.

In a morbidly obese patient with ovarian torsion, the vaginal approach may be safer, even in an emergency setting. The video case report demonstrated the key surgical

Table 4　VNOTES approach in performing myomectomy depending on location

Study	Approach	Case size	Myoma size/location	Key techniques	Outcomes	Advantages
BAEKELANDT, 2017	Traditional vNOTES	8	Types 3-7, anterior/posterior	Anterior/posterior colpotomy, glove port or commercial port, laparoscopic instruments	All cases successful, no complications, < 24 h discharge	No scars, cost-effective, adaptable to low-resource settings
LIU *et al*., 2018	Single-site vNOTES	1	6 cm anterior	Combines vaginal + single-site lap skills, anterior colpotomy, barbed suture closure	Minimal blood loss, full recovery	Expands vaginal access, improves visibility compared to traditional vaginal
SUNKARA, GUAN, 2022	Robotic vNOTES (Xi or SP)	1	8 cm posterior	Robotic port, posterior colpotomy, Extracorporeal C-incision morcellation, wristed suturing	Minimal blood loss, day surgery, V-Loc closure	Precision in suturing, deep fibroid access, fertility-sparing

steps, including detorsion, paratubal cystectomy, and salpingectomy via a posterior colpotomy. The video highlights technical tips, particularly for obese patients, while emphasizing that similar outcomes can be achieved laparoscopically if robotic access is unavailable[28].

3.2 Oncologic applications

Oncologic applications for RA-vNOTES can be limited, as tumor metastasis can occur throughout the entire abdominopelvic space. This is also true for benign pathologies such as endometriosis. This limitation restricts the use of vNOTES because access to the upper abdomen is reduced (Table 5).

However, applications within the pelvis can make vNOTES an appealing approach. In cases such as early endometrial cancer, surgical evaluation includes sentinel lymph node sampling, which can be challenging due to its location. Multiple case reports have described techniques for retroperitoneal sentinel lymph node biopsies and mapping[29-32]. In this context, it is not the visualization and dissection of the cephalad portions of the pelvis that are limited, but rather the caudal portions due to camera angling. To address this, a retroperitoneal approach was developed to improve visualization of this space. An additional benefit of this approach is the ability to perform the procedure without Trendelenburg positioning[33].

There is ongoing debate regarding the use of minimally invasive surgery in the treatment of cervical cancer, mainly due to the results from the Laparoscopic Approach to Cervical Cancer (LACC) trial. This study showed decreased overall survival at 4.5 years: 90.6% in the minimally invasive group versus 96.2% in the open surgery group. The LACC trial concluded by recommending open surgery, with minimally invasive surgery reserved for research purposes[34].

At this time, there do not appear to be any publications on RA-vNOTES for the treatment of cervical cancer; however, there are case reports for conventional vNOTES[35-36]. It has been suggested that limitations in laparoscopic training may have contributed to the results of the LACC trial[37]. Could RA-vNOTES serve as an aid for minimally invasive surgical treatment of cervical cancer?

No case reports exist for RA-vNOTES in the treatment of ovarian cancer, and there are only a few case reports for conventional vNOTES. These have mostly involved patients with borderline disease, where full staging was feasible transvaginally[38-39].

3.3 Complex and advanced cases

One contraindication to vaginal surgery is suspicion of an obliterated posterior cul-de-sac. However, in a case review of 23 patients with an obliterated posterior cul-de-sac, the procedure was found to be safe and feasible when performed by an experienced surgeon[40]. The benefits of the robotic platform include controlled dissection and cautery for establishing tissue planes. This is especially useful not only in cases with an obliterated posterior cul-de-sac but also in patients with a frozen pelvis. These advantages also apply to procedures where an abdominal approach would be more complex, such as cases involving abdominal mesh, multiple prior abdominal surgeries, or complex urologic procedures like a Mitrofanoff. The advantages of RA-vNOTES were demonstrated in a patient with a history of ruptured tubo-ovarian abscess, which caused severe, dense adhesions throughout the pelvis and abdomen. Performing RA-vNOTES allowed the hysterectomy to be completed without significant intestinal adhesiolysis.

At our institution, we conducted a retrospective case

Table 5 Oncologic applications for vNOTES

Study	Design	Approach	Key outcomes
BAEKELANDT *et al*., 2024	Prospective multicenter series (64 patients)	Conventional laparoscopic retroperitoneal vNOTES SLN dissection + hysterectomy	Median operative time was 126 min; estimated blood loss was 80 mL; bilateral SLN identification occurred in 97%; only one macrometastasis was found, with no significant complications.
COMBA *et al*., 2024	Comparative cohort (19 vNOTES vs. 38 laparoscopy)	Retroperitoneal vNOTES SLN biopsy vs. conventional laparoscopy	Operative time, blood loss, and SLN counts were similar; the vNOTES group experienced lower pain and a shorter hospital stay; no recurrences have been reported.
LIU *et al*., 2022	Case report	1 patient (32 years old, early-stage endometrial carcinoma) Robot-assisted vNOTES hysterectomy + staging	The procedure was successful with disease confined to the uterus; no complications were reported. The video demonstrates the robotic technique via natural orifice.
WANG *et al*., 2021	Single-center cohort (23 vNOTES; 51 laparoscopy)	Transperitoneal vNOTES + SLN mapping vs. laparoscopic control	SLN detection rates were approximately 96% vs. 92%; estimated blood loss and operative time were comparable. The vNOTES group had fewer complications (4.3% vs. 7.9%, $P = 0.029$) and a shorter hospital stay (3 d vs. 4 d, $P = 0.003$)

series of 274 patients undergoing RA-vNOTES hysterectomy on the da Vinci Xi and SP platforms, with additional endometriosis resection across all disease stages. The study found that while RA-vNOTES is a safe and effective approach regardless of stage, advanced endometriosis was significantly associated with longer operative times (median 222 min in stage Ⅳ vs. 138 min in stage Ⅰ, $P < 0.001$), increased hysterectomy time (median 51 min in stage Ⅳ vs. 38 min in stage Ⅰ, $P < 0.001$), greater blood loss (median 50 mL in stage Ⅲ/Ⅳ vs. 25-30 mL in stage Ⅰ/Ⅱ, $P < 0.001$), and higher conversion rates (3 conversions, all in stage Ⅲ/Ⅳ, $P = 0.03$). Despite these differences, complication rates, same-day discharge, and postoperative pain scores were comparable across all stages.

3.3.1 Urogynecology

Selecting urogynecology cases for uterine prolapse is feasible with RA-vNOTES. Several case reports (Table 6) demonstrate sacrocolpopexy performed using the RA-vNOTES approach, with LUI *et al.* describing the learning curve[41]. Both abdominal and vaginal approaches can be used for uterine suspension procedures. In vaginal surgery, the enhanced visualization and dexterity provided by robotic assistance allow precise identification of surrounding structures, such as the ureters, to ensure safe placement of suspension sutures.

All three studies in Table 6 support the technical feasibility of robotic vNOTES for sacrocolpopexy using the da Vinci Xi system, with no major perioperative complications or recurrences reported during follow-up. Robotic platforms address key limitations of standard vNOTES and single-site laparoscopy, particularly challenges in suturing, triangulation, and deep pelvic dissection. Guan *et al.* highlighted the ergonomic and technical advantages of wristed robotic instruments and 3D visualization. Operative times in RA-vNOTES cases varied significantly (132-275 min), reflecting differences in surgeon experience, patient complexity, and case setup[42-43].

Regarding expandability, the learning curve potential is evident, as MEI *et al.* reported successful implementation even by beginners. The inclusion of beginners in the MEI study is encouraging and suggests scalability of RA-vNOTES in training environments[41, 44]. However, most reports are small, single-surgeon case series, limiting broader generalizability. To validate these findings, prospective, multi-institutional studies comparing RA-vNOTES to both laparoscopic sacrocolpopexy and conventional transvaginal approaches with long-term follow-up are needed. Additionally, procedures should be incorporated into residency training by creating stepwise pathways or simulation-based models for robotic Xi vNOTES sacrocolpopexy to ensure reproducibility, especially for early adopters and residents or fellows.

3.3.2 Obesity

As mentioned earlier, vNOTES offers specific advantages when bypassing abdominal pathology. The increasing BMI in the United States has resulted in a growing number of overweight and obese patients. Table 7 presents current cases that highlight the benefits of the vNOTES approach.

Conventional and RA-vNOTES have been successfully performed in patients with a BMI up to and above 70 kg/m^2. In obese patients, vNOTES significantly reduced operative times compared to traditional abdominal laparoscopic approaches (median, 35 min vs. 125 min)[45]. Across all cases, including complex scenarios, there were no major intraoperative complications, conversions were rare, and tissue extraction techniques ensured oncologic safety. These procedures included planned hysterectomy, sterilization,

Table 6　Case reports in RA-vNOTES sacrocolpopexy

Study	Sample size	Surgical approach	Mean operative time	Key outcomes	Innovations
GUAN *et al.*, JMIG 2020	1	Robot-assisted transvaginal single-site	227 min	POP-Q 0 postoperatively; vaginal length preserved	Detailed technique highlights include wristed instruments, a 30° scope, and 3D vision
GUAN *et al.*, Urology 2021	2	Robotic vNOTES (Xi)	Not explicitly stated	Both patients were discharged on postoperative day 1 with no complications; POP-Q 0 at 3 weeks	This is the first report of using the robotic Xi platform for vNOTES sacrocolpopexy, emphasizing simplified suturing
MEI *et al.*, HELIYON 2023	10 (8 TV-NOTES, 2 RV-NOTES)	Mixed (TV-NOTES and RV-NOTES)	TV-NOTES: 275 min; RV-NOTES: 132 min	There was no mesh exposure or recurrence; procedures performed by beginners were successful	This highlights the training feasibility and potential for expanding cases to early learners

Table 7 RA-vNOTES procedures as performed on obese patients

Study	Design	Patient profile	Procedure	Key findings
LIU *et al*., 2023 (PMID 37328095)	Case report (n = 1)	BMI 70 kg/m^2, 16-week-sized uterus	Robotic vNOTES hysterectomy + bilateral salpingo-oophorectomy	Feasible and safe in extreme obesity using an air seal for exposure, lap pads, ureter identification, vessel sealing, and contained tissue extraction.
MATAK *et al*., 2024 (PMID 38557832)	Retrospective cohort (n = 24)	BMI > 30 kg/m^2, benign indications	Conventional laparoscopic vNOTES vs. total laparoscopic hysterectomy (TLH)	vNOTES had a significantly shorter median operative time (35 min vs. 125 min, P < 0.05), similar conversion and complication rates, demonstrating feasibility in the obese population.
SENDUKAS and GUAN, 2025	Case report (n = 1)	Morbid obesity, emergency torsion	Robotic vNOTES emergency detorsion	Demonstrated safe emergency use in obese patients, avoiding abdominal incisions; no complications
SUNKARA and GUAN, 2022	Case report (n = 1)	BMI > 70 kg/m^2, sterilization patient	Robotic vNOTES bilateral salpingectomy	The technique enabled precise, fine robotic handling in super-obese patients; successfully completed with no reported complications.

and emergency adnexal detorsion in morbidly obese patients[28, 46].

Certain strategies, such as adjusting air-seal insufflation pressures, strategic use of laparotomy sponges, contained tissue extraction, and robotic instrumentation adjustments, are integral considerations in obese patients[47]. A retrospective cohort study of 287 patients found that RA-vNOTES hysterectomy is a safe and effective approach for both obese and non-obese patients, with comparable outcomes in operative time, blood loss, hospital stay, and complication rates. Although hysterectomy time was significantly longer in the obese group (42 min vs. 38 min, P = 0.003), overall surgical performance remained consistent, and conversion to conventional laparoscopy was rare (1.5%)[48].

4 Advantages of robotic vNOTES

VNOTES hysterectomy has been validated by studies demonstrating shorter operative times and hospital stay with no significant differences in intraoperative or postoperative complications[13]. Additionally, patients undergoing vNOTES are typically discharged within 12 hours (77% vs. 43%), report lower visual analog scale (VAS) pain scores, require less analgesia in the first seven days after surgery, have shorter operative times (39-99 min for vNOTES vs. 72-171 min), and, if needed, spend fewer nights in the hospital (0.5 night vs. 2 nights) compared with conventional laparoscopy[49]. For adnexal cystectomies, the vNOTES approach results in less pain, shorter postoperative stays, and improved cosmesis compared with conventional laparoscopy[50]. When comparing robot-assisted single-incision laparoscopic surgery (RA-SILS) with RA-vNOTES, the vaginal approach shows a significant reduction in surgical site infections[8]. In RA-vNOTES, 84.5% of patients had no complications, and an additional 13.1% experienced Clavien-Dindo Ⅰ–Ⅱ complications, compared to complication rates of 11.68%-27.84% in the traditional vNOTES group (63a). These are some of the benefits observed in patients.

Using a robotic platform also offers benefits for the surgeon, including 3D visualization, jointed instruments, tremor control, 10 × magnification, and ergonomic positioning[51]. Currently, surgical robot platforms are being developed specifically for single-port use. The da Vinci SP, Jingfeng, and Shurui robotic platforms are designed as single arms with outlets for advancing elbowed and wristed instruments, allowing triangulation in confined spaces. Additionally, the robotic camera can articulate away from the operating field to provide a vantage point distant from the robotic instruments[19]. These benefits also apply to the transabdominal approach.

5 Challenges and limitations

With increased use of the robotic platform, there is growing interest in understanding the learning curves required to achieve proficiency, particularly in gynecology and urology. Meta-analyses and literature on this topic are difficult to interpret regarding the specific requirements for

proficiency, aside from the general principle that more prior experience leads to a shorter learning curve: "Those with greater experience required fewer procedures to overcome their learning curve"[52]. For new learners, such as residents, simulator robotic consoles provide opportunities for practice and assessment *ex vivo*, allowing a certain level of proficiency to be achieved before operating on patients[53].

RA-vNOTES faces several limitations, including the need for a dedicated robotics program, access to a robotic simulator, and the availability of preceptors or surgeons who are comfortable with vNOTES and, separately, with RA-vNOTES.

Achieving proficiency in RA-vNOTES is challenging. A high level of skill is required in single-incision procedures, robotic surgery, and vaginal surgery before attempting RA-vNOTES. After reaching baseline proficiency, additional challenges arise due to changes in the anatomical perspective when viewing the surgical field cephalad, which may obscure anatomical relationships. Complexity increases further when significant pelvic pathology is present. A case series of 84 patients demonstrated that 10 cases of RA-vNOTES were needed to achieve surgical proficiency in performing a hysterectomy, and 10-20 cases were required for port placement and robot docking. This series clearly stated that the surgeon needed experience in single-incision laparoscopic surgery as well as robotic surgery to qualify for this learning curve[53].

One of the major factors in RA-vNOTES is the upfront cost of the robot, along with annual maintenance within the context of operative expenses. Compared with conventional laparoscopy, RA-vNOTES cases cost $ 2 189 to $ 6 685 more per case. Cost is an important factor, but it should be considered alongside multiple other factors[17]. This is one example of a cost breakdown, but caution is warranted as this factor may have limited generalizability.

6 Current evidence and clinical outcomes

Substantial evidence demonstrates the benefits of conventional vNOTES and robotic assistance in surgery. However, there is currently a lack of long-term data on RA-vNOTES, with much of the available information extrapolated from conventional vNOTES studies. Additionally, research on RA-vNOTES is limited to a few groups and, consequently, a small number of publications. When comparing conventional vNOTES and RA-vNOTES, outcomes were similar, demonstrating non-inferiority[37]. Without increased risks associated with RA-vNOTES, robotic assistance can help overcome the limitations of traditional vNOTES, allowing for broader application.

Incisionless surgery with improved cosmesis and reduced infection risk are compelling reasons patients may prefer or seek a vNOTES procedure. In a study evaluating quality of life (QOL) in patients undergoing RA-vNOTES compared to robot-assisted abdominal laparoscopic surgery, patients experienced improved QOL by postoperative day 28. Using the EQ-5D-5L questionnaire, the study found that 90% of patients in the RA-vNOTES group achieved complete QOL by postoperative day 14, and 100% by postoperative day 28. In another trial measuring time to full return to work (RTW), the timeframe for laparoscopic hysterectomy ranged from three to 45 weeks. Although these are just numbers, they have real implications for patients' lives, particularly regarding return to work, which can be a significant source of stress[54].

7 Future Directions and Research Opportunities

There is a clear interest in minimally invasive and single-site surgery as robotic platforms evolve to meet this demand. With the introduction of the da Vinci SP, Jingfeng, and Shurui robotic systems, this technology is already being applied. These robots represent the present. What does the future hold? At Vanderbilt University School of Engineering, three trends have been identified.

The first trend is miniaturization and micro-robotics. This development is underway – not only for surgery, but also for drug delivery and cancer treatment. The second trend is artificial intelligence and machine learning, which are gaining momentum. These technologies are expected to assist in real-time decision-making, improve surgical planning, and enhance precision. The third trend is telepresence and global translation. This concept is not new; the first procedure was performed between New York and Strasbourg in 2002. However, it is not yet commonplace. The exciting application of this technology is the potential to perform robot-assisted procedures in remote areas,

offering benefits such as lower infection rates, same-day discharge, and quicker return to baseline quality of life.

In the past, the concept of conventional laparoscopy and those who recognized its potential in its early stages were met with skepticism. The art of vaginal surgery in the United States is being replaced by laparoscopy. In 2008, only 21% of graduating residents believed they could perform a vaginal hysterectomy. However, vNOTES may allow for a resurgence in vaginal surgery. This is becoming a reality, as the implementation of vNOTES in academic settings has led to more residents performing vaginal surgeries. This increase is attributed to the fact that vNOTES broadens the indications for vaginal surgeries. If there is ever a time to promote a procedure, it is during training. The same applies to RA-vNOTES – with the rise of single-site robotic technology, it could one day become the standard of care for pelvic surgeries.

To better define the role of RA-vNOTES in clinical practice, future studies should include well-designed randomized controlled trials with standardized outcome measurements (including cost, pain, and ergonomics) and stratification by surgeon experience to provide robust, generalizable evidence. Additionally, further research should explore training pathways and learning curves for RA-vNOTES to promote its safe integration into broader surgical practice.

In conclusion, robot-assisted vNOTES has advanced over the last decade, providing improved visualization and maneuverability in the pelvis, which has benefited both surgeons and patients.

* * *

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