



Robotic versus laparoscopic enucleation of ovarian endometriotic cysts with pathological analysis of inadvertent follicular loss

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Abstract

Ovarian endometrioma cystectomy may compromise ovarian reserve through inadvertent excision of ovarian cortex. We compared inadvertent cortical removal between robotic-assisted and conventional laparoscopic cystectomy using digital pathology. We retrospectively analyzed 81 patients (40 laparoscopic, 41 robotic) who underwent single-surgeon cystectomy (January 2020–December 2025) with digitized hematoxylin and eosin–stained slides available. Ninety-eight ovary/side specimens were classified as follicle-containing cortex, cortex without follicles, or fibrosis, and excised cortical area (mm²) was quantified. The primary analysis used log-linear regression adjusted for cyst length and width with patient-clustered robust standard errors. Tissue-type distribution did not differ by approach ($P=0.611$). Excised cortical area was smaller with robotics (median 34.6 mm², interquartile range 16.9–82.3) than laparoscopy (median 65.4 mm², interquartile range 39.5–81.6; $P=0.011$). In the adjusted model, robotics was associated with a smaller excised cortical area (robot-to-laparoscopy ratio 0.55, 95% confidence interval 0.32–0.93; $P=0.029$). Follicle counts and antral follicle presence among follicle-containing specimens were comparable. Robotic-assisted cystectomy was associated with less inadvertent excision of ovarian cortex after accounting for cyst dimensions, while follicle-based specimen metrics did not differ.

Keywords Ovarian endometrioma · Laparoscopic surgery · Robotic surgery · Digital pathology · Ovarian cortex · Ovarian reserve

Abbreviations

AFC	Antral follicle count
AMH	Anti-Müllerian hormone
ASRM	American Society for Reproductive Medicine
BMI	Body mass index
CI	Confidence interval
H&E	Hematoxylin and eosin
IQR	Interquartile range
IPW	Inverse probability weighting
OR	Odds ratio

Background

Endometriotic cysts of the ovaries are one of the most common presentations of endometriosis, occurring in up to 40% of women with the condition and up to 50% of women with infertility [1]. While endometriotic cysts frequently cause clinical symptoms including dysmenorrhea, pelvic pain, infertility, and potential increased risk of malignant transformation, the surgical intervention of these ovarian lesions

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presents a crucial clinical dilemma: the need to adequately remove the ectopic endometrial tissue within the ovarian tissue while losing less ovarian reserve at the same time [2–4]. There is compelling evidence demonstrating that surgical excision (cyst enucleation) of endometriotic cysts, no matter how meticulous, is paradoxically linked to significant impairment of ovarian reserve [5]. This consequence may compromise future fertility and potentially accelerate reproductive aging [6].

The mechanisms underlying this iatrogenic tissue damage during ovarian surgery are regarded as being multifactorial. During enucleation of ovarian cysts and adhesiolysis, unintended removal of healthy ovarian tissue represents one critical pathway to follicular or ovarian volume loss, as endometriotic cysts are infiltrative in nature and the cyst pseudo-capsules often lack distinct clean histological boundaries from the surrounding tissues [7]. Histopathological examination of specimens from ovarian cyst enucleation consistently indicates that recognizable ovarian tissue exists adjacent to the cyst wall in over 90%, containing follicles of all stages. In addition to mechanical stripping, vascular compromise and thermal injury during hemostasis, as well as postoperative inflammation/edema, may contribute to acute and subacute follicle loss [8, 9].

These observations have led some clinicians to defer endometrioma surgery before assisted reproduction unless cyst size/location or refractory pain warrants intervention. However, the possibility of spontaneous pregnancy restoration and effective pain amelioration after surgical intervention argues compellingly to find an optimized surgical modality which minimizes iatrogenic ovarian damage [2]. Advancement of technology in surgical instrumentation has led to robotic-assisted platforms, the most widely used being the da Vinci Surgical System. Robotic surgical systems offer ergonomic advantages over conventional laparoscopy, where articulation of the robotic tools provide more freedom of motion, three-dimensional binocular visualization with magnification, enhanced precision accompanied by tremor filtration and less surgeon fatigue [10, 11]. However, there is little evidence in the literature supporting the actual benefits of utilizing the robotic armament in preventing unwanted follicle loss during ovarian cyst enucleation [12].

Direct microscopic quantification of ovarian cortex and follicles inadvertently attached to the excised cyst wall provides granular insight into technique-related tissue loss [7, 12]. Using standardized analysis of digitized H&E slides, we aimed to determine whether robotic assistance—via enhanced visualization and instrument control—translates into reduced inadvertent excision of ovarian cortex and follicle-bearing tissue compared with conventional laparoscopy.

Methods

Study population

The study was performed at the Department of Obstetrics and Gynecology, Yongin Severance Hospital, Yonsei University Medical Center, encompassing a total of 81 patients (40 laparoscopic and 41 robotic) who received either da Vinci robotic (Xi or SP) or conventional laparoscopic enucleation (cystectomy) of endometriotic cysts between January 2020 and December 2025. Only cases performed by a single gynecologic surgeon for both robotic and laparoscopic surgery were enrolled to avoid inter-surgeon technical variability. The operating surgeon had extensive experience in minimally invasive gynecologic surgery, including more than 1,600 da Vinci Xi/SP cases and more than 6,000 laparoscopic cases over 13 years at a university center. A retrospective analysis of the pathologic slides was performed to compare the amount (area) of attached follicle-containing healthy ovarian cortical tissue surrounding the pseudo-capsule of the enucleated endometriotic cysts. Patients were excluded if they had concomitant ipsilateral ovarian pathology other than endometrioma, suspected or confirmed malignancy/borderline tumor, pregnancy at the time of surgery, prior ovarian surgery, hormonal suppression (oral contraceptives or other agents such as progestins/dienogest or GnRH agonist/antagonist) within 3 months before surgery, or were younger than 20 years or older than 38 years.

Ethical consideration

The study was approved by the Institutional Review Board of Yongin Severance Hospital and conducted in accordance with the Declaration of Helsinki (IRB No. 9-2026-0013). The requirement for informed consent was waived due to the retrospective design.

Surgical procedures

Robotic surgery was performed using either the da Vinci Xi multiport platform or the da Vinci SP single-port platform. In Xi cases, a transumbilical multichannel port was placed at the umbilicus for camera and assistant access, and two additional robotic working ports were placed bilaterally 8 cm lateral and 2 cm caudal to the umbilicus. In SP cases, a single transumbilical multichannel port was inserted through the umbilicus, through which the robotic camera, robotic instruments, and assistant access were introduced. In conventional Anthrex laparoscopy, a three-port technique was used, consisting of a 5-mm 30° umbilical camera port and two 5-mm working ports placed at the McBurney and

contralateral McBurney points. Standard laparoscopic bipolar forceps and monopolar scissors or a monopolar hook were used for dissection, with grasping forceps or Allis forceps for traction; a laparoscopic needle holder was used when hemostatic suturing was required. Specimens were retrieved in an endoscopic bag through the umbilical port/incision.

Robotic cases used bipolar forceps, monopolar curved scissors or a monopolar hook, a wristed needle driver, and a ProGrasp or Cadere forceps; laparoscopic cases used standard bipolar forceps, monopolar scissors or hook, and grasping forceps, including Allis forceps when stronger traction was required. Across all approaches, cyst enucleation began with the smallest feasible cortical incision at the thinnest identifiable ovarian cortex after adhesiolysis. Traction-countertraction was used to identify the least vascular cleavage plane, and the dissection plane was re-routed when the initial plane appeared suboptimal. Hydrodissection with saline injected through an intraperitoneal needle was used when feasible, although it was often limited in densely infiltrative endometriomas. Energy use was minimized throughout dissection. After enucleation, hemostasis was first attempted with gentle compression using hemostatic gauze. Bipolar coagulation was restricted to pinpoint application for focal bleeding away from the ovarian hilum or infundibulopelvic ligament, whereas broader oozing areas were managed with tension-free 3–0 polyglactin (Vicryl) sutures. The hemostatic strategy did not materially differ between the Xi and SP platforms.

Histologic analysis

The specimens were transferred immediately to the pathology department for gross examination and fixation. After tissue fixation, hematoxylin and eosin-stained tissue slides were digitized using the Philips Fast Scanner (Philips Electronics, The Netherlands) and analyzed. Whole-slide imaging enabled full-slide review on screen with digital annotation of ovarian cortical boundaries and automated calculation of annotated area, allowing more standardized and reproducible quantification than manual visual estimation by conventional light microscopy [13]. The pathological review and initial annotations were performed by a single pathologist specialized in gynecologic and breast pathology, with secondary quality-control review by another pathologist in a randomly selected subset of cases. A representative slide containing the highest tissue area with the least fragmentation from each case of endometriotic cyst enucleation was screened first for the presence or absence of ovarian cortical tissue attached to the cystic wall. One representative slide per case, the slide containing the largest cortical tissue area with the least fragmentation, was selected because

the number of paraffin blocks and slides varied across cases according to cyst size and specimen fragmentation; this approach was used to standardize comparisons across cases. The specimens were classified into the following three categories: (1) endometriotic cyst with attached ovarian cortical tissue containing follicles; (2) endometriotic cyst with attached ovarian cortical tissue but without follicles; and (3) endometriotic cyst specimen with predominant fibrosis (fibrotic tissue) without identifiable follicles. For those with ovarian cortical tissue attached, the total area of attached ovarian cortical tissue was obtained by delineating the cortical tissue areas on the digitized slide and summing the areas. The ovarian cortical tissue showing follicles embedded within was analyzed further for the total number of follicles observed, ranging from primordial to antral. Follicle density was determined by obtaining the ratio of the number of follicles per ovarian cortical tissue area (mm^2). Cortical tissue delineation was performed at $\times 50$ or $\times 100$ magnification, follicle counting at $\times 200$, and follicle classification at $\times 200$ or $\times 400$. For reproducibility assessment, a random quality-control subset of approximately one in five cases was independently reviewed by a second pathologist from the same institution.

Sample size

The sample size calculation was based on the preliminary data presented by Sinha et al. (2024) [12], using a two-sided independent samples t-test with $\alpha = 0.05$, $\beta = 0.20$ (80% power), and assuming a moderate standardized effect size (Cohen's $d = 0.68$) (approximately corresponding to a difference of 3 follicles between groups), resulting in a minimum sample size of 35 per group. To account for an approximately 10% anticipated specimen inadequacy and planned subgroup analyses by bilateral versus unilateral disease, we aimed to enroll at least 40 patients per group. With 40 patients per group, the planned sample size provides approximately 85% power for $d = 0.68$ under these assumptions.

Statistical analysis

The analysis combined two cohorts: conventional laparoscopy (lapa) and robot-assisted surgery (robot). Patient-level variables (e.g., age, BMI, preoperative AMH, ASRM stage, cyst length/width, and bilaterality, and exploratory clinical outcomes) were summarized at the patient level. Digital pathology outcomes (tissue type and follicle metrics) were analyzed at the ovary/side specimen level (left or right). Because some patients contributed bilateral specimens, regression models for specimen-level outcomes used cluster-robust standard errors clustered at the patient level.

Continuous variables were summarized as median (interquartile range [IQR]) and compared between groups using the Mann–Whitney U test. Categorical variables were summarized as n (%) and compared using the chi-square test or Fisher's exact test, as appropriate. Exploratory patient-level clinical and fertility-related outcomes included estimated blood loss, perioperative hemoglobin change (preoperative minus postoperative hemoglobin), perioperative complication, transfusion, 30-day readmission, reoperation, documented recurrence, chart-documented pregnancy intention, and documented pregnancy among patients with pregnancy intention when available. All tests were two-sided; $P < 0.05$ was considered statistically significant and values < 0.001 are reported as $P < 0.001$.

Tissue type categories were defined as described in the Histologic analysis section (type 1: follicle-containing cortex; type 2: cortex without follicles; type 3: predominant fibrosis). For follicle-related outcomes, blank antral follicle counts were treated as zero when tissue type was known. Blank total follicle counts were treated as zero for tissue types 2 or 3, and treated as missing for tissue type 1 to avoid conflating missing entry with a true zero. Cystic follicle counts were available only in the robotic cohort and were summarized descriptively. Because tissue type 2 (without follicles) may reflect both surgical technique and low baseline ovarian reserve, multivariable models prioritized adjustment for age and preoperative AMH.

The primary outcome was ovarian cortical area (mm^2) measured in the excised specimen. Because cortical area was right-skewed, it was log-transformed. The prespecified primary model was a log-linear regression: $\log(\text{cortical area}) = \beta_0 + \beta_1(\text{robot vs. lapa}) + \beta_2 \cdot \log(\text{cyst length}) + \beta_3 \cdot \log(\text{cyst width})$. Exponentiated coefficients $\exp(\beta_1)$ are reported as the robot-to-laparoscopy ratio (ratio < 1 indicates smaller excised cortical area in the robot cohort). Pre-specified additional adjustments included age, bilaterality, and ASRM stage (modeled as categorical). Because excised cortical area can scale with cyst size, cyst length and width were included as covariates in the primary model (log-transformed) to adjust for lesion size.

Secondary outcomes included: (i) the probability that a specimen contained follicle-bearing tissue (tissue type 1 vs. others); and among tissue type 1 specimens, (ii) the presence of any antral follicle (binary), and (iii) follicle and antral

follicle counts. Binary outcomes were modeled using logistic regression with patient-clustered standard errors. Count outcomes were modeled using Poisson regression with an offset of $\log(\text{cortical area})$ to estimate density (counts per unit area). Age and preoperative AMH were included as covariates to partially account for baseline ovarian function.

Sensitivity analyses included [1] restricting analyses to ASRM stage 4 cases; and [2] inverse probability weighting (IPW) to address differential availability of cortical area measurements between cohorts. For IPW, the probability of having cortical area recorded was modeled using logistic regression including surgery type, age, ASRM stage, $\log(\text{cyst length})$, $\log(\text{cyst width})$, and bilaterality. Stabilized weights were applied to the primary cortical-area model, and weights were additionally trimmed at the 1st and 99th percentiles in a robustness check.

Statistical analyses and figure generation were performed using R version 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria), with complete-case inclusion for each model.

Results

Study population and data completeness

The analytic cohort included 81 patients (40 lapa and 41 robot) contributing 98 ovary/side specimens (44 lapa and 54 robot). Among the robotic cohort, 34/41 (82.9%) underwent surgery with the da Vinci SP platform and 7/41 (17.1%) with the da Vinci Xi platform. Tissue type classification was available for all included specimens by design. Cortical area was recorded in 37/44 (84.1%) lapa specimens and 49/54 (90.7%) robot specimens.

In the evaluated cohort, age, BMI, and preoperative AMH did not differ materially between groups (Table 1). The robot cohort had more advanced disease by ASRM stage (median 4.0 vs. 3.0; $P = 0.008$) and larger cyst length (median 4.65 vs. 4.00 cm; $P = 0.031$).

Pathology tissue type and follicle metrics

Representative histologic examples illustrating cortical tissue delineation, tissue-type classification, and follicle

Table 1 Baseline characteristics

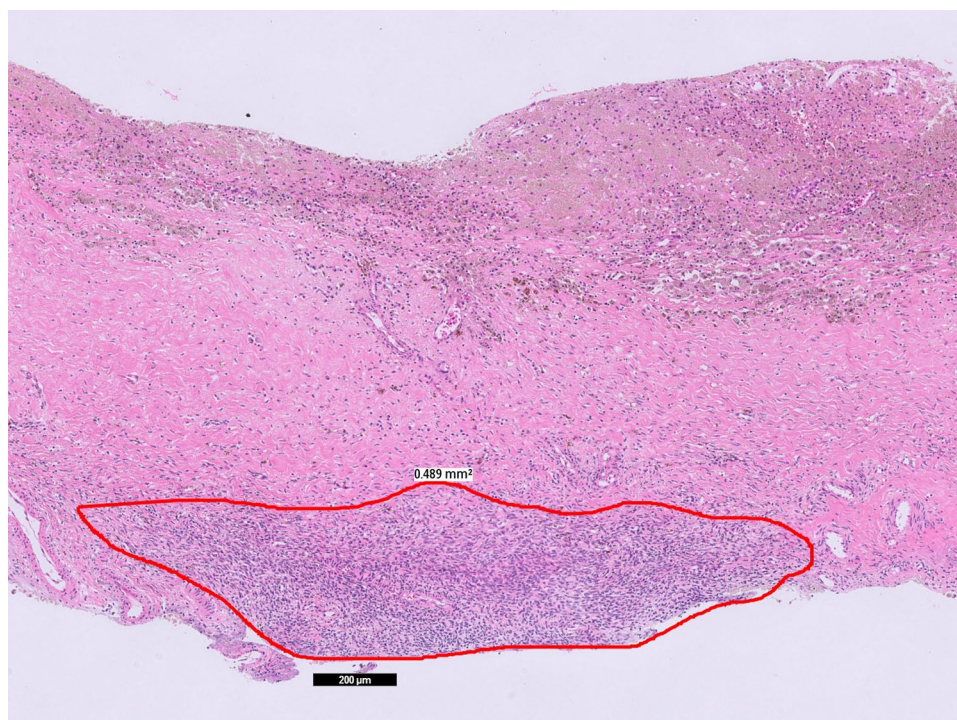
Variable	Lapa (median [Q1,Q3]) (n=40)	Robot (median [Q1,Q3]) (n=41)	P value
Age, years	29.50 [27.00, 36.25]	30.00 [25.00, 33.00]	0.457
BMI, kg/m ²	20.91 [19.61, 22.47]	21.39 [19.51, 24.43]	0.529
Preoperative AMH	2.96 [1.47, 4.97]	3.54 [2.00, 4.93]	0.435
ASRM stage	3.00 [3.00, 4.00]	4.00 [4.00, 4.00]	0.008
Cyst length, cm	4.00 [3.00, 5.00]	4.65 [3.50, 6.12]	0.031
Cyst width, cm	2.60 [2.00, 4.00]	3.35 [2.00, 4.05]	0.425
Bilateral disease	9/40 (22.5%)	16/41 (39.0%)	0.149

subtype identification are shown in Figs. 1, 2 and 3. Tissue type distribution did not differ between surgical approaches (chi-square $P=0.611$; Table 2). Follicle-bearing tissue (type 1) was observed in 86.4% of lapa specimens and 79.6% of robot specimens. Among type 1 specimens, follicle count and antral follicle metrics were similar across groups (Table 2). In adjusted logistic regression, the odds of type 1 tissue were not significantly different for robot vs. lapa after adjustment for age (OR 0.61, 95% CI 0.20–1.80; $P=0.370$). In the age+AMH model, higher preoperative AMH was associated with increased odds of type 1 tissue (Supplementary Information: Table S1). In this quality-control subset, no material discrepancies affecting cortical-area delineation or follicle counting were identified on secondary review.

Primary outcome: ovarian cortical area

The excised cortical area was smaller in the robot cohort (median 34.55 mm², IQR 16.94–82.30) compared with lapa (median 65.42 mm², IQR 39.48–81.59; $P=0.011$; Table 2 and Fig. S1). In the primary log-linear model adjusting for cyst length and width (both log-transformed), robot-assisted surgery was associated with a lower cortical area (robot-to-lapa ratio 0.55, 95% CI 0.32–0.93; $P=0.029$). The association was consistent after additional adjustment for age (ratio 0.55; $P=0.040$) and after further adjustment for bilaterality and ASRM stage (ratio 0.52; $P=0.027$) (Table 3 and Figs. S2–3).

Fig. 1 Ovarian cortical tissue delineated. The area of ovarian cortical tissue attached on the outer surface of the endometriotic cyst was carefully delineated (x50)



Sensitivity analyses

In ASRM stage 4 cases only, the association remained in the same direction but was borderline significant (ratio 0.53, 95% CI 0.29–0.99; $P=0.054$; Table 3). IPW analyses addressing differential recording of cortical area yielded similar estimates (IPW primary ratio 0.55, 95% CI 0.32–0.93; $P=0.030$), and results were robust to trimming extreme weights (ratio 0.54, 95% CI 0.31–0.92; $P=0.026$; Table 3).

Additional perioperative and exploratory follow-up outcomes are summarized in Supplementary Table S2. Estimated blood loss was higher in the robotic group, although concomitant myomectomy was also more frequent in robotic cases. Other short-term safety outcomes and postoperative hormonal treatment variables were broadly similar between groups. Recurrence and pregnancy-related data were based on chart documentation during nonuniform follow-up and should be interpreted descriptively.

Discussion

In this study, we applied digital pathology–based quantification of ovarian tissue inadvertently excised during ovarian endometrioma cystectomy and compared robotic-assisted versus conventional laparoscopic approaches. The principal finding was that the cortical area present in the excised cyst wall specimen was smaller in the robotic cohort, and this association persisted after adjustment for cyst size and other

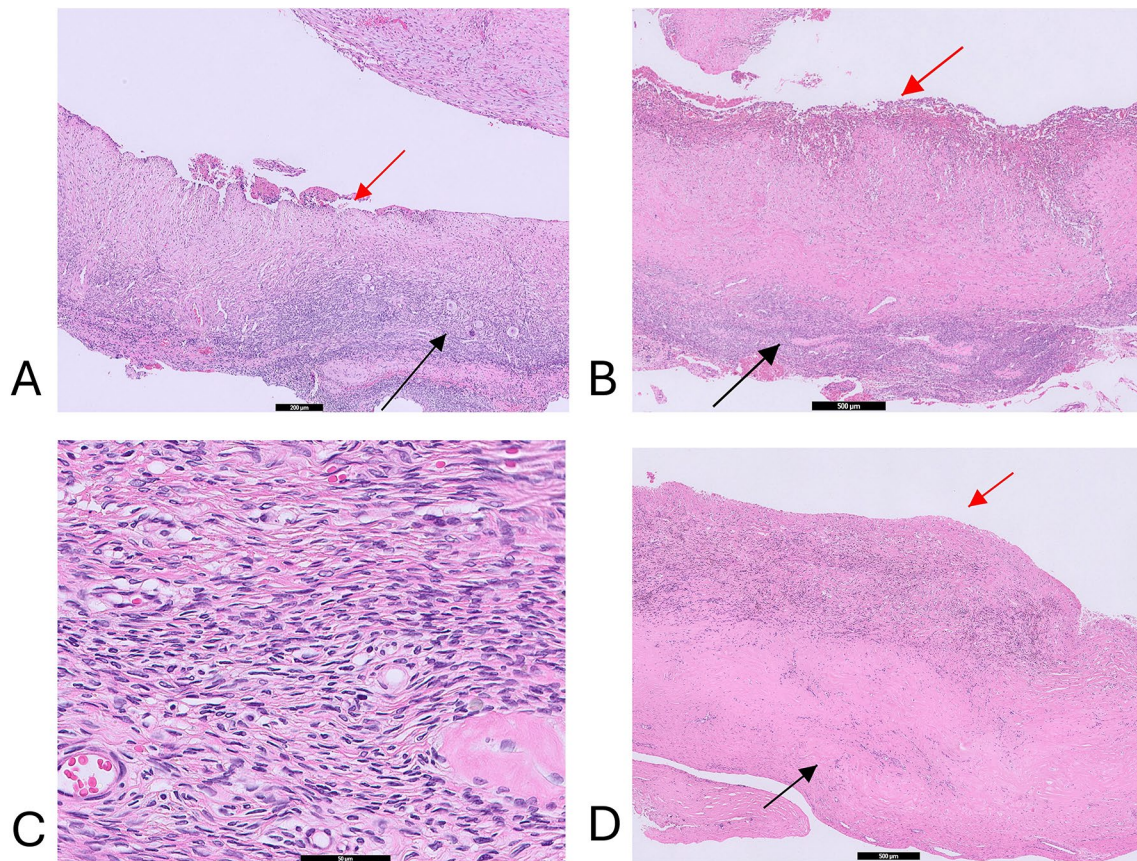


Fig. 2 Ovarian tissue type. **A** Ovarian cortical tissue containing follicles (mainly primordial, black arrow) was classified as tissue type 1 (x50). The luminal surface of the endometriotic cyst is noted (red arrow). **B** Ovarian cortical tissue without follicles (black arrow) was classified as tissue type 2 (x20). The luminal surface of the endometriotic cyst is noted (red arrow). **C** The cortical tissue shows no identifiable

follicle within the ovarian cortical tissue in tissue type 2 (x400). **D** The endometriotic cyst wall is sole composed of hyalinized fibrotic tissue with inflammatory cells and vessels without any ovarian tissue attached (black arrow, x20). The luminal surface of the cyst is noted (red arrow)

clinically relevant covariates. In contrast, the distribution of tissue-type categories (follicle-containing cortex vs. follicle-absent cortex vs. fibrosis) and follicle subtype counts (including antral follicles) did not differ significantly by surgical approach. Together, these results suggest that robotic assistance may reduce inadvertent removal of ovarian cortex, while the follicular content of the excised specimen—a metric influenced by both the surgical dissection plane and baseline ovarian reserve—may be less sensitive to surgical approach in a real-world cohort.

Ovarian reserve is commonly assessed in clinical practice using serum anti-Müllerian hormone (AMH) and ultrasound-based antral follicle count (AFC), which reflect the remaining follicular pool and correlate with ovarian responsiveness [14]. However, interpreting these biomarkers in the setting of ovarian surgery requires nuance. Serum AMH represents the combined contribution of both ovaries; therefore, following unilateral surgery, systemic AMH is not side-specific and may incompletely capture ipsilateral tissue loss, particularly when contralateral function is preserved [15,

16]. Moreover, AFC measurement is susceptible to cycle-to-cycle fluctuation and operator dependence. Standardization statements have emphasized uniform acquisition and reporting, yet variability remains [17]. These limitations provide strong rationale for direct specimen-based quantification of inadvertent ovarian tissue loss, as performed in the present study using digital pathology.

Prior studies have shown that ovarian endometrioma cystectomy can be associated with a substantial reduction in ovarian responsiveness. In a paired IVF-cycle analysis comparing operated versus contralateral intact ovaries after unilateral endometrioma excision, Somigliana et al. reported a mean 53% reduction in dominant follicle development in the previously operated ovary [18]. Ragni et al. further suggested that this impairment reflects predominantly quantitative rather than qualitative injury, with reduced numbers of follicles/oocytes/embryos but similar fertilization and embryo quality measures [19]. Systematic reviews and meta-analyses consistently demonstrate post-operative AMH decline after stripping cystectomy [6, 20].

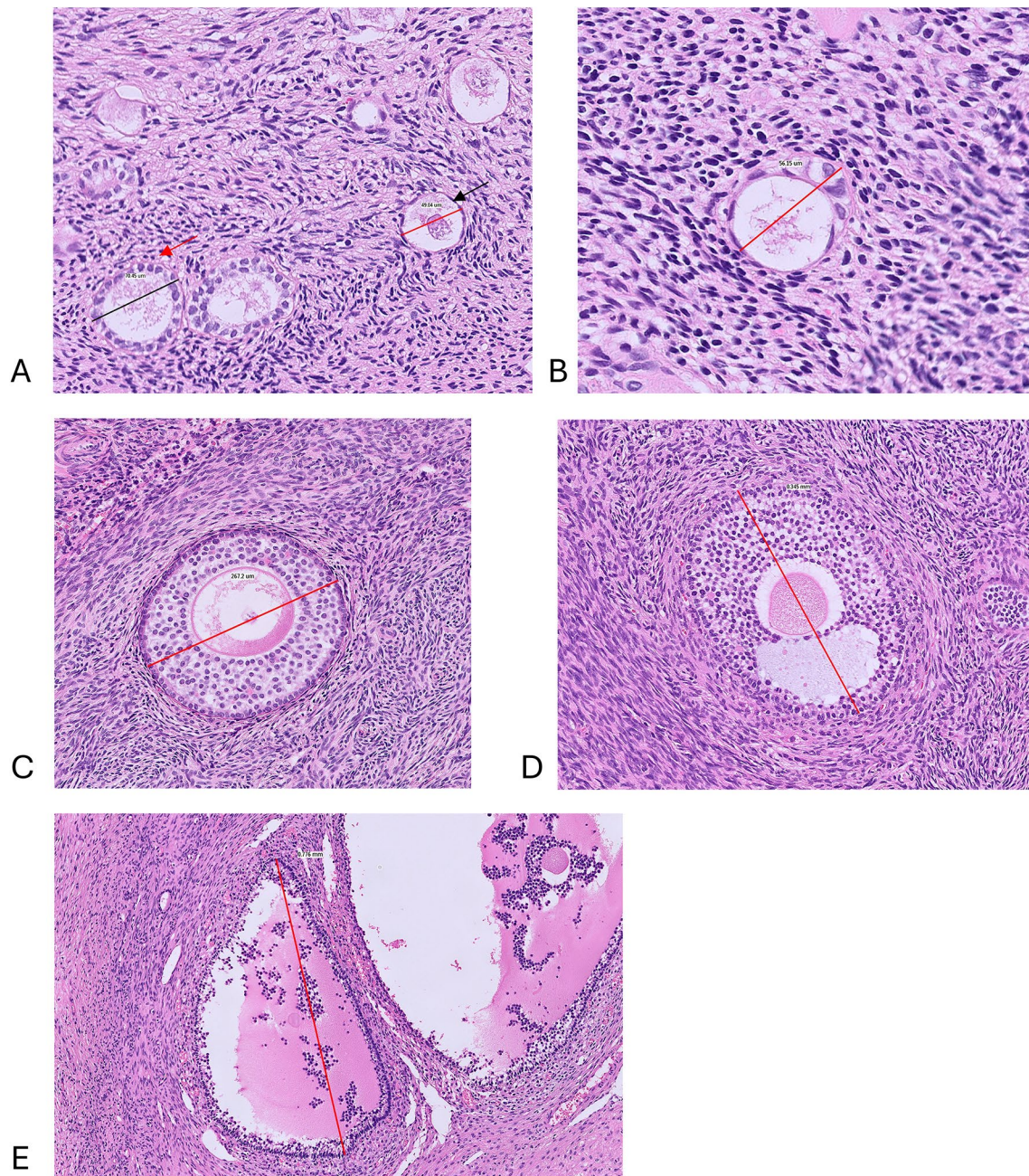


Fig. 3 Ovarian follicle types identified within tissue type 1. **A** Primordial and primary follicles (x400). The black arrow shows a primordial follicle with a single layer of squamous granulosa cells and the red arrow shows a primary follicle with a single layer of cuboidal granulosa cells. **B** Intermediate primordial follicle (x600) with a single

layer of squamous and cuboidal cells. Late primary follicle (x400) surrounded by multiple layers of cuboidal cells. **D** Small antral follicle (x200). **E** Antral follicle (x100) with more than 50% of the follicle showing antrum

Importantly, ovarian reserve compromise appears greater in bilateral disease in comparative syntheses [20], although bilaterality does not necessarily translate into worse IVF/ICSI outcomes in all post-cystectomy series [21]. When AMH and AFC were evaluated concurrently in the same women, AMH declines were consistently detected across postoperative windows whereas AFC changes were smaller

and less consistent [22]. Together, these data highlight that excised cortical area is best interpreted as a surrogate histologic endpoint of iatrogenic ovarian tissue loss, which may complement but does not directly substitute for functional outcomes such as AMH, AFC, pregnancy, or live birth.

Robotic-assisted surgery may offer technical features—stable three-dimensional visualization, articulated

Table 2 Pathology findings (specimens with tissue type)

Outcome	Lapa (<i>n</i> =44)	Robot (<i>n</i> =54)	<i>P</i> value
Tissue type 1 (with follicle)	38 (86.4%)	43 (79.6%)	0.611
Tissue type 2 (without follicle)	4 (9.1%)	6 (11.1%)	
Tissue type 3 (fibrosis)	2 (4.5%)	5 (9.3%)	
Cortical area (mm ²), median [IQR] (area recorded)	65.42 [39.48, 81.59] (<i>n</i> =37)	34.55 [16.94, 82.30] (<i>n</i> =49)	0.011
Cortical area in tissue type 1 only (mm ²), median [IQR]	67.08 [50.73, 81.62] (<i>n</i> =35)	39.60 [26.43, 96.02] (<i>n</i> =42)	0.062
Follicle count in tissue type 1, median [IQR]	16.5 [5.0, 77.5] (<i>n</i> =34)	23.5 [11.0, 38.5] (<i>n</i> =42)	0.810
Antral follicle count in tissue type 1 (0 included), median [IQR]	0.00 [0.00, 0.75] (<i>n</i> =38)	0.00 [0.00, 1.00] (<i>n</i> =43)	0.952
Antral follicle present in tissue type 1, n/N (%)	10/38 (26.3%)	12/43 (27.9%)	1.000

Table 3 Primary outcome regression (exp(beta)=Robot/Lapa ratio)

Model	Robot/Lapa ratio	95% CI	<i>P</i> value
Unadjusted (log area~surgery)	0.529	0.316–0.887	0.016
Primary: +log(cyst L)+log(cyst W)	0.546	0.321–0.929	0.029
Primary+age	0.550	0.313–0.964	0.040
Primary+age+bilateral+ASRM stage	0.518	0.292–0.916	0.027
Sensitivity: stage 4 only (primary)	0.534	0.287–0.995	0.054
Sensitivity: IPW (primary)	0.545	0.318–0.934	0.030
Sensitivity: IPW trimmed (1st–99th pct, primary)	0.535	0.312–0.919	0.026

instruments, and improved ergonomics—that could facilitate a more precise dissection plane and reduce inadvertent inclusion of normal cortex. Evidence supporting this hypothesis has begun to emerge. Sinha et al., using artificial intelligence–assisted whole-slide imaging to quantify tissue loss in excised specimens, reported that robotic assistance reduced ovarian tissue loss, particularly in bilateral disease and with increasing cyst size [12]. Our findings are concordant with respect to area-based tissue loss, but we did not observe consistent between-group differences in follicle counts or antral follicle presence. This pattern supports the interpretation that excised cortical area may be a more stable surrogate of inadvertent ovarian tissue removal than follicle counts alone in retrospective cohorts, where follicle-based endpoints are sparse and biologically heterogeneous.

The absence of between-group differences in follicle subtype counts and tissue-type categories warrants careful interpretation. Follicles observed within excised cyst wall specimens are not purely a marker of surgical technique; they are also influenced by baseline ovarian reserve, patient age, AMH, endometrioma-related cortical distortion, and the thickness of the cyst wall–cortex interface. In clinical terms, “no follicles detected” may reflect successful cleavage along the correct plane, but may also occur when the patient’s follicle density is intrinsically low. Accordingly, follicle-related endpoints should be interpreted as “mixed” signals reflecting both operative performance and ovarian biology, and adjusted analyses incorporating age and preoperative AMH are important to reduce confounding. In line with this interpretation, preoperative AMH was independently associated with the presence of follicle-containing tissue (type 1) in adjusted analysis.

We view cortical area within the excised specimen as a surrogate histologic marker of iatrogenic ovarian tissue removal and a complementary, pathology-grounded indicator of tissue-sparing surgery, rather than a direct functional measure of postoperative ovarian reserve or fertility potential. Unlike serum AMH—which reflects systemic granulosa-cell activity from both ovaries—specimen cortical area directly captures the physical quantity of cortex removed from the operated side. However, whether a smaller excised cortical area translates into improved AMH, AFC, pregnancy, or live-birth outcomes remains uncertain and requires prospective validation. Thermal damage from hemostasis and devascularization may impair remaining tissue without increasing the amount of cortex present in the specimen. Randomized trials have evaluated hemostatic strategies (e.g., bipolar coagulation vs. suturing) with variable effects on postoperative ovarian reserve markers [8, 23], highlighting that tissue-sparing dissection and tissue-preserving hemostasis likely operate in parallel.

The clinical implications of minimizing iatrogenic ovarian damage are substantial. Surgery for ovarian endometrioma can improve pain and may reduce recurrence, yet concerns about diminished ovarian reserve have prompted ongoing debate regarding surgical timing and the role of proceeding directly to assisted reproduction in selected patients. Contemporary guidelines emphasize individualized decision-making, balancing symptom control and fertility goals, and recognize the need to minimize ovarian injury when surgery is undertaken [3]. This emphasis on fertility-aware, tissue-sparing surgery is consistent with broader trends in benign gynecologic surgery away from unnecessarily radical treatment [24], while long-term patient-centered outcomes such

as pain relief and quality of life remain essential alongside pathologic endpoints [25].

This study has strengths. First, it leverages digital pathology to quantify tissue endpoints in an objective and reproducible manner, addressing limitations of clinical biomarkers and ultrasound measures. Second, specimen-level analyses accounted for within-patient correlation, and sensitivity analyses adjusted for cyst dimensions and disease severity.

Nevertheless, several limitations should be acknowledged. First, the retrospective, nonrandomized design limits causal inference. Baseline differences between groups—notably in ASRM stage and cyst size—together with the incomplete availability of cortical area measurements, particularly in the laparoscopic group, may have introduced selection bias. Although multivariable adjustment and inverse probability weighting were performed, residual confounding is still likely. Learning-curve bias is another potential concern in any retrospective single-surgeon comparison. In the present study, however, laparoscopic and robotic cases were performed during the same study period by a surgeon with extensive experience in both minimally invasive platforms, making a major platform-level learning-curve effect less likely. Even so, subtle temporal changes in case selection, operative judgment, or procedure-specific technique cannot be fully excluded. The predominance of SP cases within the robotic cohort likely reflects nonrandom platform selection for adnexal surgery in reproductive-age women, in whom a transumbilical single-incision approach may be attractive because it minimizes visible abdominal scarring. Accordingly, the present findings should be interpreted as comparing a predominantly SP robotic cohort with conventional laparoscopy, rather than as a platform-specific comparison between the Xi and SP systems. In addition, other unmeasured factors, including specific dissection and hemostasis techniques and specimen handling, may also have contributed to the observed differences. Although the initial annotations were performed by a single specialized pathologist, a random quality-control subset was cross-checked by a second pathologist without material discrepancies; nevertheless, formal full-cohort interobserver agreement statistics were not available. In addition, to standardize comparisons across cases with variable block numbers and tissue fragmentation, cortical area was quantified from one representative slide per case; therefore, the total amount of inadvertently excised cortex across all blocks may have been underestimated. Finally, because systemic ovarian reserve and fertility outcomes were not uniformly available longitudinally, the extent to which reduced excised cortical area translates into improved postoperative ovarian function requires prospective validation. Accordingly, these findings should be interpreted as pathology-based evidence

of reduced inadvertent cortical excision using a surrogate histologic endpoint, rather than direct proof of improved long-term ovarian reserve or fertility outcomes. Future studies should integrate specimen-based metrics with standardized ovarian reserve testing, symptom/quality-of-life outcomes, fertility endpoints, and emerging biomarker-based phenotyping approaches [26].

Conclusion

In conclusion, robotic-assisted cystectomy was associated with reduced inadvertent excision of ovarian cortex as measured by excised cortical area, while follicle-based specimen metrics did not differ consistently between approaches. These findings support the potential for robotic assistance to reduce iatrogenic ovarian tissue loss, particularly relevant for patients with fertility goals, bilateral disease, or larger cysts. Prospective studies incorporating standardized reserve assessment and longer-term reproductive outcomes are warranted to confirm clinical benefit.

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Declarations

Competing interests The authors declare no competing interests.

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Consent to Participate The requirement for informed consent was waived by the IRB due to the retrospective nature of the study and the use of de-identified data/specimens.

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