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REVIEW

# Robot-assisted retroperitoneal lymph node dissection in testicular cancer: state of the art and future perspectives

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## Abstract

Robot-assisted retroperitoneal lymph node dissection (R-RPLND) is an increasingly adopted minimally invasive option for carefully selected patients with testicular germ-cell tumours. We performed a narrative (non-systematic) review of retrospective single- and multicentre cohorts from high-volume programmes to appraise peri-operative safety, functional preservation, and oncologic control in primary and post-chemotherapy settings. In primary disease (typically clinical stage I–IIA/B), representative medians across series from expert centres include estimated blood loss of ~ 50 to 200 mL, hospital stay of 1–2 days, and nodal yields of ~ 19 to 32; major complications (Clavien–Dindo ≥ III) are uncommon (~ 0 to 10%), and antegrade ejaculation is usually preserved (often ≥ 85 to 100%) when nerve-sparing templates are applied. In post-chemotherapy cohorts—generally limited to smaller, peripherally located residual masses with favourable biology—robotic RPLND is feasible but technically demanding, with reported conversion rates of ~ 0 to 13% and major complication rates of ~ 10 to 20%; chylous complications remain a notable risk. Across available retrospective comparative series, including propensity-matched cohorts, R-RPLND has been associated with lower estimated blood loss and shorter hospitalisation than open RPLND (for example, ~ 200 vs 300 mL and 1 vs 5 days in a matched primary cohort; ~ 235 vs 825 mL and 2 vs 7 days in post-chemotherapy series), at the cost of longer operative time, while nodal yields and short-term oncologic outcomes appear comparable; these non-randomised data are descriptive and subject to selection and centre bias rather than proof of causality. For carefully staged seminoma IIA/B (≤ 3 cm nodes), contemporary guidelines permit RPLND as a chemotherapy-sparing option (Moderate recommendation; Evidence Level B), consistent with phase II data showing high 2–3-year disease control after primary RPLND. Centralisation and experience are critical: population-based analyses suggest fewer in-hospital complications and shorter hospital stays with robotic cases, and learning-curve data show improving efficiency and safety as programmes mature. Overall, when undertaken by experienced teams in high-volume centres, R-RPLND offers low blood loss, short hospitalisation, favourable ejaculatory outcomes, and low in-field recurrence for appropriately selected patients, while requiring judicious case selection and a low threshold for conversion in technically demanding post-chemotherapy disease.

**Keywords** Robotic surgery · Retroperitoneal lymph node dissection · Testicular cancer · Minimally invasive surgery

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## Introduction

Retroperitoneal lymph-node dissection (RPLND) remains a cornerstone of contemporary testicular germ-cell tumour (TGCT) care because it serves a dual purpose: it provides definitive pathologic staging of retroperitoneal disease while offering curative extirpation in well-selected patients, thereby informing—and sometimes obviating—adjuvant systemic therapy [1, 2]. In Stage I–II non seminomatous TGCT (NSGCT)—and, under carefully circumscribed conditions, in low-volume Stage II seminoma (for which the AUA guideline provides a Moderate recommendation, Evidence Level B) current guidelines explicitly position RPLND as a guideline-concordant option within shared decision-making, with strong emphasis on delivery at high-volume referral centres to optimize safety, nerve-sparing, and oncologic quality [1–4].

Beyond routine pathways, open RPLND retains a central role in select, high-stakes scenarios. These include growing teratoma syndrome, where complete resection is the only curative therapy [5, 6], and post-chemotherapy RPLND for persistent markers with anatomically resectable disease [7, 8]. Other indications are re-operative RPLND for retroperitoneal relapse [9] and definitive nodal clearance in extragonadal retroperitoneal GCT [10]. It is also an option for carefully selected seminoma cases with FDG-avid or > 3 cm residual masses, where management hinges on multidisciplinary review [11]. Over the last two decades, the technique has evolved to minimize morbidity while preserving ejaculatory function. Meticulous, template-based nerve-sparing can maintain antegrade ejaculation for most selected men. This anchors functional outcomes as a primary objective alongside cancer control [12]. Laparoscopy demonstrated the potential for such de-escalation but was ultimately limited by challenging ergonomics and suturing demands.

The advent of robot-assisted RPLND (R-RPLND) has altered this balance. It offers high-definition 3-D optics and wristed instrumentation to facilitate precise, haemostatic dissection around the great vessels and sympathetic chains, thereby supporting nerve-sparing templates [13–15]. Early experiences reported acceptable blood loss, short hospital stays, and encouraging short-term oncologic outcomes [14, 15]. As experience matured, programs refined their techniques to balance radicality with function. This iterative process involved adjusting port placement, patient positioning, and dissection templates, as reflected in learning-curve analyses [16, 17]. The opportunities and caveats of R-RPLND are now widely acknowledged. The procedure may enable treatment de-intensification strategies, but most evidence derives from retrospective cohorts in expert centres rather than from randomized trials. This evidence is marked by significant heterogeneity in indications, surgical techniques, and the extent of dissection. Such variation complicates conventional data pooling, meaning that interpretation requires a framework that integrates technique, patient selection, and program-level experience.

In this context, a narrative review is methodologically appropriate, as it allows integration of technical nuance, learning-curve effects, and programme-level factors within the IDEAL framework for surgical innovation. Our aim is to provide an up-to-date narrative synthesis of R-RPLND for testicular germ-cell tumours, focusing on: (1) peri-operative outcomes and complications in primary and post-chemotherapy settings; (2) oncologic efficacy and patterns of recurrence; (3) functional outcomes, particularly preservation of antegrade ejaculation; (4) principles of patient selection and operative technique; and (5) future perspectives including technological advances, training, and centralisation of care in high-volume centres.

## Methods

The review was structured in line with best-practice guidance for narrative reviews and the IDEAL framework for surgical innovation [18–22], with an explicit research question, a justified search strategy, and a transparent description of study selection and synthesis. We did not perform a formal PRISMA-ScR scoping review or meta-analysis. Given substantial heterogeneity in case mix (primary vs post-chemotherapy, unilateral vs bilateral templates, primary vs salvage indications), selection criteria, and reporting of outcomes, we used a grouped narrative synthesis, organising results by clinical setting, study design (single-arm vs comparative), and centre volume. Data quality was appraised qualitatively by considering sample size, single-versus multicentre design, use of propensity matching or multivariable adjustment, maturity of follow-up, and whether outcomes reflected early learning-curve experience or established practice. Where comparative peri-operative figures are cited, they are interpreted as descriptive associations rather than causal estimates.

We included original retrospective or prospective series reporting robot-assisted RPLND for testicular germ-cell tumours with extractable peri-operative and/or oncologic outcomes. Case reports, purely laparoscopic series, studies without a robotic subgroup, and reports focused exclusively on non-oncologic indications were not summarised in the main outcome tables. When available, comparative studies of open versus robotic RPLND, including propensity-matched or otherwise adjusted cohorts, were highlighted but not pooled quantitatively.

We searched MEDLINE (via PubMed) and Embase from January 2000 to September 2025 using combinations of the terms “testicular cancer”, “germ cell tumour”, “retroperitoneal lymph node dissection”, “RPLND”, “robotic”, “robot-assisted”, “post-chemotherapy”, and “seminoma”. We restricted the search to human studies, adults, and English-language full-text articles and supplemented database searches by screening reference lists of key articles and relevant guideline documents, as well as studies known to the authors through clinical and academic practice.

This review was designed as a narrative (non-systematic) synthesis of the contemporary literature on robot-assisted retroperitoneal lymph node dissection (R-RPLND) in testicular germ-cell tumours.

## Results

### Evolution of clinical evidence and outcomes

In the past two decades, growing evidence has established the feasibility and safety of R-RPLND in testicular cancer. The first proof-of-concept case demonstrated the technical viability of robotic dissection in an 18-year-old patient [23]. Subsequent early series from multiple centres confirmed that a robotic approach could successfully replicate traditional RPLND with minimal morbidity. For example, an initial case series reported by Cheney et al. in a mixed primary and post-CT setting on 18 patients achieved complete resections in low-stage NSGCT patients with no open conversions or transfusions, a median lymph node yield of ~ 20, and rapid convalescence at a mean follow-up of 22 months [24]. Another group introduced a single-dock supine technique to enable bilateral template dissection robotically in the post-chemotherapy setting [25].

R-RPLND was soon extended to more advanced scenarios: Kamel et al. described 12 post-chemotherapy cases (including residual masses up to 7.5 cm) performed robotically with acceptable operative times (~ 5 h), moderate blood loss (~ 475 mL), and only one major complication, and notably observed no cancer relapses at a median follow-up of 31 months [26]. An Indian institutional series similarly found that robot-assisted resection of post-chemotherapy residual tumours was feasible in 13 patients, yielding a median 20 lymph nodes with no recurrence seen over a median follow-up of 23 months (range 3–58), although 31% of patients (4/13) developed chyle leak complications, reflecting a need for refined lymphatic management [27].

As techniques evolved, perioperative outcomes remained consistently favourable. Staged comparisons showed that robotic cases experienced dramatically less blood loss, shorter hospitalization, and quicker convalescence than historical open surgery cohorts [28]. A single-surgeon prospective series of 100 RPLNDs (28 robotic vs 72 open) including primary and post-chemotherapy patients, in a matched-cohort analysis, reported significantly reduced median blood loss (50 mL vs 400 mL, $p < 0.00001$), operative time (150 vs 195 min, $p = 0.023$), and length of stay (1 day vs 5 days, $p < 0.00001$) in the robotic group, with a lower incidence of post-operative anejaculation, while complication rates were statistically equivalent and oncologic outcomes were indistinguishable between approaches [29]. Similarly, a German single-centre report noted that R-RPLND conferred shorter operative duration, reduced hospital stay, and fewer high-grade complications compared to open RPLND, without any increase in recurrence risk [17, 30]. A nationwide analysis of US hospital data further echoed these advantages: among 44 robotic and 319 open primary RPLNDs, robotic surgery was associated with significantly fewer in-hospital complications (0% versus 17%, $p < 0.001$) and a shorter median stay (1 day vs 4 days, $p < 0.001$), and overall costs were equivalent when the reduced length-of-stay was accounted for [31].

More recently, a propensity score–matched analysis from a high-volume tertiary centre compared open and robotic primary RPLND for clinical stage II disease. In the matched cohort (26 robotic vs 38 open procedures), relapse-free survival did not differ significantly between approaches and no in-field recurrences were observed in either group over a median follow-up of 23.5 months. Robotic cases had shorter hospital stay (median 1 vs 5 days) and lower estimated blood loss (median 200 vs 300 mL), at the cost of longer operative time (8.8 vs 4.3 h), underscoring that peri-operative advantages are achievable in carefully selected patients within experienced programmes [32].

Oncologically, the robotic approach has shown intermediate-term efficacy comparable to open surgery. In a large series of primary R-RPLND (N = 58, clinical stage I–II), with a median follow-up of 19 months (IQR: 12–26), the 2-year recurrence-free survival was 91%, with all five relapses occurring outside the dissected template (e.g. in the lungs or pelvis) and not within the retroperitoneum [33]. That multi-centre study reported a median of 26 nodes removed per patient and only a 3% intraoperative complication rate, underscoring that meticulous nodal dissection can be achieved robotically without excess morbidity [33]. Another multi-institutional analysis of 49 men undergoing primary R-RPLND, with a median follow-up of 15 months (IQR: 8–24), found similarly high nodal yields (median 32) and low perioperative complication rates; only four patients (8%) experienced a recurrence (just one in-field) and only 18% required adjuvant chemotherapy for occult metastases, suggesting that upfront minimally invasive surgery can spare many patients the toxicity of systemic therapy [34].

The robotic approach has also been successfully employed in the post-chemotherapy setting across multiple centres [35]. A two-centre Dutch study in a cohort of 45 men in a post-chemotherapy setting with a median follow-up of 28 months (IQR: 14–41), achieved complete excisions with an 11% conversion rate and only two minor complications, yielding a 98% 2-year recurrence-free survival—outcomes on par with open post-chemotherapy series [36, 37]. In France, Branger et al. reported on 66 post-chemotherapy RA-RPLNDs from four centres, noting only three conversions (~5%) and no Clavien grade ≥ IIIb complications; at a median follow-up of 16 months (IQR: 10–25), just two patients (3%) had relapsed (both outside the retroperitoneum), demonstrating that carefully selected advanced cases can be managed robotically without compromising short-term cancer control [38, 39].

Notwithstanding these positive outcomes, authors have emphasized prudent case selection for robotic surgery. A German comparative study highlighted that post-chemotherapy robotic cases carry higher technical difficulty: in a cohort of 23 patients (14 post-CT), all 7 intraoperative complications, all 4 conversions to open, and all 4 transfusions occurred in the post-chemotherapy subgroup, whereas none of these occurred during primary RA-RPLNDs, leading the authors to advise reserving robotic surgery for smaller, peripheral residual masses and experienced robotic surgeons [40]. Consistent with this, a population-based Swedish series found that only roughly one-third of all referred testicular cancer RPLND candidates were ultimately suitable for a robotic approach based on stringent selection criteria (primarily tumour bulk), but those who did undergo R-RPLND (N = 34, mixed primary and post-CT) had no intra-field recurrences and significantly faster recoveries at a median follow-up of 22.5 months, at the cost of a somewhat higher incidence of chylous complications [41].

Functional outcomes and preservation of fertility have been an important focus of these studies. One early single-surgeon series noted that two patients (11% of the total cohort, N = 19) developed retrograde ejaculation following bilateral full-template robotic dissections, reflecting the risk to sympathetic nerves when both sides are resected [13]. A contemporary analysis of 22 unilateral post-chemotherapy RA-RPLNDs with a median follow-up of 32 months (range 12–48) still observed retrograde ejaculation in ~ 14% of patients (3/22) and new-onset erectile dysfunction in another ~ 14%, underlining that even nerve-sparing unilateral surgery can impact sexual function in a subset of men [42]. Nonetheless, with refined nerve-sparing techniques, most patients maintain normal ejaculatory function: for instance, in a multi-centre study of primary R-RPLND where modified unilateral templates were predominantly used, all evaluable patients (N = 44) retained antegrade ejaculation [14]. In general, rates of long-term complications such as persistent anejaculation appear lower with robotic surgery than historically reported with open surgery, likely owing to the facilitation of meticulous nerve preservation. A 2022 systematic review encompassing 42 studies (459 patients in single-arm series and 3763 in comparative series) concluded that R-RPLND offers acceptable perioperative outcomes in both primary and post-chemotherapy settings, with conversion rates of approximately 2% and 9%, respectively, and significantly lower transfusion requirements (0.9 vs 14.5%) and overall complication rates (7.8 vs 18.5%) compared to open RPLND, albeit with the caveat of selection bias in comparing cohorts [43]. Importantly, none of the series in the review found any compromise in oncological efficacy attributable to the robotic approach [43]. However, the learning curve remains evident: in one recent Chinese single-centre comparison of 47 primary RPLNDs, the robotic subgroup had a higher incidence of high-grade (Clavien III–IV) complications (28.6%) than both the laparoscopic and open surgery groups, even though oncologic and andrologic outcomes were comparable—a disparity the authors attributed to early surgeon experience and which they suggest may diminish with improved proficiency [44].

Beyond germ cell tumours, the robotic technique has shown promise in related indications. Surgeons have applied R-RPLND in the management of low-volume metastatic seminoma as a chemotherapy-sparing strategy; in a combined Norwegian-Swedish cohort of 62 such patients managed surgically, 40 underwent R-RPLND with excellent outcomes (24-month progression-free survival ~ 90% and no significant increase in morbidity), supporting surgery as an option in select seminoma cases to avoid long-term chemo toxicity [11]. Additionally, extended robotic retroperitoneal dissections have been reported for select cases of metastatic upper tract urothelial carcinoma, demonstrating that the robotic platform can be utilized for complex retroperitoneal oncologic surgery beyond testis cancer when performed by experienced surgeons [45].

Finally, the first multi-institutional outcomes comparing robotic vs open post-chemotherapy RPLND in a randomized setting are still awaited, but current retrospective data suggest that in centres with the appropriate expertise, R-RPLND can achieve equivalent cure rates with significantly reduced perioperative morbidity. A recent large international series of 144 patients (53 robotic, 91 open) observed that robotic surgery led to significantly shorter hospitalization (median 3 vs 7 days, $p < 0.001$), less intraoperative blood loss (median 100 vs 300 ml, $p < 0.001$), and faster convalescence (e.g. earlier drain removal and less analgesic requirement), with no significant difference in complication rates relative to open surgery, while maintaining similar lymph node yields and relapse-free survival at 2 years [46].

In summary, the reviewed studies collectively indicate that R-RPLND is a feasible and effective alternative to open surgery for both primary low-stage and post-chemotherapy testicular cancer in appropriately selected patients. R-RPLND offers the benefits of reduced blood loss, shorter hospital stay and convalescence, and lower rates of complications such as ileus, transfusion, and post-operative pain, without compromising oncologic outcomes in the intermediate term [45]. Ongoing refinements in patient selection, surgical technique (e.g. nerve-sparing templates, single-dock approaches), and accumulation of longer-term follow-up data will further clarify the role of R-RPLND, but current evidence supports its use as a safe option that can improve perioperative recovery and potentially preserve ejaculation in the majority of patients while achieving cancer control equivalent to the gold-standard open approach [46]. Where comparative figures (robot vs open) are cited without confidence intervals or *p*-values, they should be interpreted as descriptive rather than inferential.

## Indications for R-RPLND

### Primary RPLND in testicular cancer

R-RPLND is increasingly utilized as a primary treatment option for well-selected men with clinical stage I or low-volume stage II NSGCT who wish to avoid chemotherapy. In this setting, surgical management provides definitive histopathologic staging and can be curative for microscopic retroperitoneal metastases. Early multi-institutional series established the feasibility and safety of primary R-RPLND, demonstrating adequate lymph node yields and low perioperative morbidity [14]. Notably, robotic dissection can detect occult metastatic disease in a substantial subset of patients; for example, in one cohort 42% of men undergoing primary R-RPLND had pathologically positive nodes, highlighting the staging benefit of upfront surgery [34]. Critically, the nerve-sparing techniques possible with robotics help preserve ejaculation, an important advantage for young patients. In experienced centres, primary R-RPLND has been embraced as a form of treatment de-escalation for low-volume disease, offering cancer control with reduced long-term toxicity compared to adjuvant chemotherapy [34]. Emerging evidence even supports a role in seminomatous tumours: a phase II trial in stage IIA/B seminoma reported that primary RPLND is feasible and can achieve initial disease control in this population when performed by expert surgeons in a multidisciplinary setting [47]. Proper patient counselling is essential, emphasizing that rigorous surveillance will follow surgery and that delayed chemotherapy may be recommended if high-risk pathology is found.

### Post-chemotherapy and salvage RPLND

The robotic approach is also being extended to select post-chemotherapy patients with residual retroperitoneal masses, though open surgery remains standard in challenging cases. Ideal candidates for robot-assisted post-chemotherapy RPLND are those with residual tumours of moderate size in favourable locations and without extensive fibrosis or vascular encasement on imaging. In this context, complete resection of residual disease (often teratoma or persistent carcinoma) is critical for long-term cure. Early adopters of robotic post-chemotherapy RPLND demonstrated that with meticulous planning, the approach is technically achievable and oncologically effective in well-chosen cases [48]. A recent multi-centre study of 66 patients reported that robot-assisted residual mass resection was safe with low conversion rates and no compromise in cancer control, as all relapses occurred outside the dissection template [38]. These findings underscore that oncology principles must trump surgical approach—conversion to open surgery is performed unhesitatingly if needed to ensure complete resection. Consequently, institutions offering robotic salvage RPLND typically establish strict selection criteria and “bailout” thresholds (e.g. unresectable fibrosis or major vascular involvement) beyond which a planned open surgery is preferred [40]. Beyond germ cell tumours, there have been exploratory reports of applying R-RPLND to other retroperitoneal malignancies. For instance, a single-surgeon series included a few cases of robotic dissection for nodal recurrence of upper tract urothelial carcinoma, suggesting technical feasibility in highly selected non-germ cell scenarios [45]. Such uses remain rare and investigational; the consensus is that R-RPLND should be practiced within its oncologic limits and not at the expense of cancer control. Programs are advised to introduce new indications cautiously, tracking outcomes to ensure they match the standards established in testicular cancer.

## Surgical technique and operative considerations

### Patient positioning and robotic setup

Proper positioning and port placement are fundamental to a successful R-RPLND. Most centres employ a flank lateral decubitus position with the table gently flexed, which uses gravity to mobilize the bowel away from the great vessels and target templates. This lateral approach permits single-docking of the robot, providing stable access from the renal vessels to the iliac bifurcation without the need for patient repositioning [49]. Trocar layout is carefully choreographed: a camera port is typically placed just above the umbilicus, and robotic instrument ports are arranged to allow adequate triangulation and range of motion while avoiding external arm collisions. Accessory assistant ports are added for suction, clip appliers, and specimen retrieval as needed. The robotic surgical cart is docked from the patient's back side in the flank position, aligning the camera arm with the aorto-caval plane. A standardized docking checklist and intra-operative time-out are used to ensure all arms have full range of motion and that instruments can be exchanged without interference. Establishing a reproducible setup is crucial, as it reduces variability during the learning curve and minimizes ergonomic hazards to patient and staff [15]. Once docking is completed, steep Trendelenburg is generally not required in the lateral position, which helps maintain cardiorespiratory stability throughout the case.

### Dissection technique and nerve-sparing

The surgical dissection in R-RPLND follows open RPLND principles but is enhanced by the magnified three-dimensional view and articulating instruments. Dissection usually begins with identification of key landmarks: the ipsilateral ureter is exposed and preserved, and the colon is reflected medially to unveil the retroperitoneal space. The lymphatic packet is approached within well-defined boundaries (modified template or full bilateral dissection depending on indication), and dissection proceeds in a cranial-to-caudal direction. Robotic instrumentation allows precise control around great vessels; for example, the wristed instruments facilitate safe skeletonization of the inferior vena cava and aorta when securing lumbar vessels or controlling small feeding arteries. Throughout the dissection, particular attention is paid to preserving the sympathetic nerve chains and hypogastric plexus fibres that run along the aorta and within the interaortocaval region. The surgeon carefully applies a nerve-sparing template when oncologically appropriate—this means limiting dissection lateral to the contralateral ureter or below the inferior mesenteric artery for unilateral cases, thereby protecting nerves that mediate ejaculation. When enlarged nodes are encountered, the robotic tools permit meticulous sharp dissection and counter-traction to maintain clean planes around the mass. Vascular control is obtained early for bulky post-chemotherapy nodes (e.g. controlling lumbar veins or gonadal vessels before mass mobilization) to prevent avulsion injuries. Lymphatic channels are clipped or sealed methodically during node packet removal to reduce the risk of chyle leak. At specimen retrieval, the nodal packet is often placed in an impermeable sack and removed via an expanded port site to maintain oncologic integrity. Each specimen is labelled according to its template or side for accurate pathological mapping. These refined techniques have been codified in high-volume centres and shown to be reproducible, enabling consistent node yields and low complication rates even as complexity of cases increases [13]. In essence, robotic technology serves as an enabling tool—the surgeon's adherence to RPLND oncologic principles remains the true determinant of success. In most contemporary series, formal intraoperative neuromonitoring is not routinely employed; instead, surgeons rely on magnified visualisation of consistent anatomical landmarks such as the postganglionic sympathetic chains along the anterolateral vertebral bodies, the intermesenteric plexus around the inferior mesenteric artery, and the hypogastric plexus fibres coursing towards the aortic bifurcation. Selected high-volume programmes have reported the adjunctive use of neuromonitoring for bilateral or reoperative dissections, but this remains the exception rather than the rule.

### Platform enhancements and learning curve

Advances in robotic systems and accumulation of surgeon experience have markedly improved the efficiency of R-RPLND over the past decade. Modern robotic platforms feature refined instrument dynamics that reduce external collisions and enable quicker re-docking and repositioning. As surgeons progress along the learning curve, operative times tend to decrease significantly while maintaining or improving surgical thoroughness. A recent single-surgeon analysis of 30 R-RPLND cases demonstrated a clear learning curve inflection after roughly 20 cases—later cases had significantly shorter operative duration and hospital stay compared to the first cases [30]. Notably, complication rates also appeared to decline with increasing experience, and no catastrophic complications occurred even early on [30]. This suggests that a careful mentorship and proctoring approach for new robotic surgeons can mitigate risk during the initial learning phase. Protocolization of the procedure further aids learning: using fixed port schemes, stepwise dissection checklists, and predefined criteria for conversion to open help standardize R-RPLND. Institutions have found value in team repetition—involving the same anaesthesiologists, nursing staff, and assistants—to streamline intraoperative workflow and reduce avoidable delays. Regular video review and case debriefings are also employed to convert tacit knowledge into teachable improvements. Taken together, the combination of improved technology and accumulated surgical wisdom has made R-RPLND safer and more efficient now than in its early adoption period. Continual auditing of outcomes (operative time, blood loss, lymph node count, etc.) is encouraged to ensure that growing experience indeed correlates with maintained oncologic quality and patient benefit. With structured training and volume, experienced programs report that R-RPLND can be performed within timeframes and outcomes comparable to open surgery, validating it as an effective approach in specialized centres [17, 30].

## Peri-operative and oncologic outcomes

### Peri-operative outcomes

The peri-operative performance of R-RPLND has been favourable when measured against open RPLND benchmarks, particularly with respect to intra-operative blood loss, transfusion requirements, and length of stay. Multiple retrospective series and matched comparisons report markedly lower median estimated blood loss and shorter hospitalisation with the robotic approach, at the price of somewhat longer operative times during the early learning curve, while conversion to open surgery remains infrequent and is usually a reflection of appropriate intra-operative judgement in technically hostile post-chemotherapy cases. From a health-systems perspective, robot-assisted surgery carries higher per-case operating room costs and, importantly, substantial fixed acquisition and maintenance expenses for the robotic platform. Economic analyses suggest that, in high-volume centres, these costs may be partially offset by downstream savings from fewer complications and shorter hospitalisations, but this balance is highly context dependent and less favourable in low-volume or resource-limited settings. A population-based study, for example, found that while R-RPLND had higher surgical supply costs, the overall in-hospital complication rate was lower (0 vs 17%) and the median length of stay shorter (1 vs 4 days), which could translate to cost-neutrality or net benefit when the entire episode of care is considered [31]. As more data accrue, especially from large database efforts such as the GRAND study, the cost-effectiveness of R-RPLND will be further clarified in the context of its clinical advantages; however, any apparent peri-operative or economic benefit must be interpreted in light of the non-randomised nature of available comparisons, preferential selection of more favourable cases for the robotic approach, and pronounced learning-curve effects (see "Limitations and risk of bias in the literature" section). Detailed study-level peri-operative and oncologic outcomes across published R-RPLND series are summarised in Supplementary Table 1.

### Oncologic efficacy

Oncologic outcomes from the R-RPLND series to date indicate that cancer control is not compromised by the minimally invasive approach when strict surgical templates are followed. Intermediate-term follow-up of both primary and post-chemotherapy robotic cases has shown durable retroperitoneal tumour control comparable to historical open results. Key oncologic endpoints include sufficient lymph node yield, pathology of resected nodes, recurrence patterns, and need for adjuvant therapy. R-RPLND can achieve lymph node counts in the 20–30+ range, similar to open dissections, signifying a comprehensive clearance of nodal tissue [48]. The distribution of pathology in post-chemotherapy R-RPLND mirrors open series: for example, among 43 robotic PC-RPLND patients, pathology revealed roughly 55% necrosis, 37% teratoma, and 7% viable carcinoma, indicating effective resection of residual disease [48]. Critically, reported recurrence rates after R-RPLND have been low. In a 2-year outcomes report from a high-volume centre, only 3 of 27 patients (11%) experienced relapse after R-RPLND, and only one relapse was within the original dissection field [50]. Other multi-centre experiences likewise note that most recurrences, if they occur, happen at distant or out-of-field sites, suggesting the robotic dissection adequately clears the targeted nodal regions [38]. For primary RPLND patients who do relapse, it is usually due to occult disease outside the template or in other organs, rather than failure to resect within the template. Moreover, the absence of in-field recurrences in many series attests to the oncologic completeness of properly executed robotic templates. The need for adjuvant chemotherapy after primary R-RPLND has been infrequent, reserved for cases with extensive occult metastases or adverse pathology; most patients can be managed with surveillance post-surgery if pathology is favourable. While follow-up durations are still relatively short in the literature (often 2–3 years), the data so far reinforce that R-RPLND provides oncologic outcomes on par with open surgery in specialized settings. Ongoing surveillance of these cohorts will determine long-term outcomes, but early indicators are that survival and cure rates remain excellent when robotic surgery is applied within appropriate oncologic boundaries. However, these reassuring results are drawn almost entirely from retrospective, non-randomised cohorts in which patients selected for R-RPLND typically have more favourable disease profiles and are treated in high-volume centres, so oncologic non-inferiority relative to open RPLND remains inferred rather than definitively proven.

The largest multicentre series of robotic post-chemotherapy RPLND to date included 173 patients treated across 11 academic centres worldwide, of whom 159 underwent pure robotic dissection and 14 required conversion to open surgery. Median estimated blood loss, operative time, and hospital stay were 100 mL, 300 min, and 2 days, respectively, and final pathology showed necrosis or fibrosis in 40%, teratoma in 49%, and viable germ-cell tumour in 11%. At a median follow-up of 22 months, eight patients had relapsed (three in-field, including one port-site recurrence), and the 4-year recurrence-free survival was 93%, supporting acceptable intermediate-term oncologic control in selected post-chemotherapy patients while highlighting the persistent risk of in-field failure and the need for longer follow-up [51]. Consequently, the apparent equivalence between robotic and open post-chemotherapy RPLND in contemporary series should be interpreted in the context of these selection effects and the pronounced surgeon and institutional learning curves discussed in "Limitations and risk of bias in the literature" section (Table 1).

### Functional outcomes

Preservation of long-term fertility and sexual function is a paramount concern in testicular cancer survivors, and R-RPLND was in part developed to maximize nerve-sparing to this end. The most significant functional issue is retrograde ejaculation resulting from damage to the sympathetic nerves that control emission of semen. Robotic visualization aids in identifying and avoiding these autonomic fibres, and early results suggest the majority of patients maintain antegrade ejaculation after R-RPLND, especially when unilateral or modified templates are employed. In a contemporary series focusing on sexual outcomes after unilateral post-chemotherapy R-RPLND on 22 patients, only about 14% of patients (3/22) developed complete retrograde ejaculation at a median follow-up of 32 months (range 12–48), while the remainder had preserved or only mildly diminished ejaculatory function [42, 52]. Even in bilateral template dissections, a multi-institutional report on post-chemotherapy R-RPLND found that 57% of evaluable patients (12/21) retained ejaculation [48]. Patients should nonetheless be counselled pre-operatively about the risk of ejaculatory dysfunction, and sperm banking is recommended prior to RPLND (robotic or open) as a precaution. Erectile function is typically expected to remain intact since the parasympathetic innervation for erection is not directly affected by the dissection; however, some patients do report transient erectile difficulty or decreased firmness, possibly related to pelvic floor trauma or psychological factors. In the series by Tufano et al., about 13% of men had a measurable decline in erectile function scores at 1 year, although most remained potent with or without medical assistance [42]. Importantly, some patients in that study achieved natural paternity after R-RPLND, underscoring that fatherhood is very much possible post-surgery. Comparative data suggest the robotic approach yields equal or better functional outcomes than open RPLND, likely due to reduced traction and clearer nerve visualization. For instance, a single-surgeon primary R-RPLND experience on 13 patients reported that 100% of them maintained antegrade ejaculation at a median follow-up of 13.2 months, highlighting what is achievable with meticulous nerve-sparing technique [53]. Moving forward, prospective collection of patient-reported outcomes is needed to fully quantify quality of life after R-RPLND. At present, the evidence is reassuring: when performed with care for nerve preservation, R-RPLND allows most young men to retain normal sexual function and fertility potential, which is a critical component of survivorship in testicular cancer care. Study-level functional and ejaculatory outcomes reported across contemporary series are summarised in Supplementary Table 2.

## Patient selection and pre-operative considerations

### Ideal candidates

Proper patient selection is the cornerstone of success in R-RPLND. Ideal candidates are those with limited volume retroperitoneal disease, favourable tumour biology, and a strong preference to avoid the morbidity of alternative treatments (like chemotherapy). For primary R-RPLND, this

**Table 1** Summary of key peri-operative, oncologic, and functional differences between primary and post-chemotherapy R-RPLND in contemporary series

| Parameter | Primary R-RPLND | Post-chemotherapy R-RPLND |
|---|---|---|
| Typical case profile | Clinical stage I–IIA/B non-seminomatous GCT or carefully selected stage IIA/B seminoma; unilateral, small-volume nodal disease with normalised tumour markers | Residual retroperitoneal masses after cisplatin-based chemotherapy, usually limited in size and located peripherally or away from major vessels, with normalised or plateauing tumour markers |
| Median estimated blood loss | Approximately 50–200 mL across contemporary series | Approximately 100–475 mL; higher values reported in cohorts including bulkier or more fibrotic masses |
| Median length of stay | Typically 1–2 days | Typically 2–3 days |
| Conversion to open surgery | Uncommon (around 0–5% in high-volume series) | Higher (around 5–13%), largely in technically complex, fibrotic, or centrally located residual masses |
| Major complications (Clavien≥III) | Approximately 0–10%, with low rates in experienced centres | Approximately 10–20%, reflecting greater case complexity and adjunctive procedures |
| In-field retroperitoneal recurrence | Very low; most reported recurrences occur outside the dissected template (e.g. lung or pelvic nodes) | Low but present; occasional in-field recurrences and rare port-site events reported in mixed series |
| Antegrade ejaculation | Preserved in the vast majority of patients (often≥85–100%) when unilateral or modified nerve-sparing templates are used | Preserved in most but with lower rates (~60 to 85% in series including bilateral templates and post-chemotherapy cases) |

typically means men with clinical stage I NSGCT who have high-risk features for occult metastasis (or stage IIA disease with small volume nodes), normal tumour markers after orchiectomy, and disease confined to one side of the retroperitoneum on imaging. In such cases, primary RPLND provides definitive staging and potential cure, appealing to patients who accept surgical risks in exchange for potentially sparing chemotherapy. Notably, there is growing interest in applying primary RPLND to seminoma in select situations. The PRIMETEST trial recently investigated primary RPLND in stage II seminoma and demonstrated that surgical management is feasible with meticulous technique and yields acceptable short-term outcomes in this traditionally chemo- or radiation-managed disease [47]. While longer follow-up is needed, this study suggests an evolving role for RPLND as part of de-escalation strategies in seminoma when done at expert centres [47]. For post-chemotherapy R-RPLND, ideal candidates are those with residual masses typically < 5–6 cm, located away from critical vascular structures, and ideally where pre-surgery imaging suggests mostly resectable teratoma or necrosis rather than extensive viable cancer encasing vessels. Patients should be in good overall condition and preferably treated at institutions with a high volume of RPLND experience. Across both primary and post-chemo scenarios, institutional policies often set minimum volume thresholds for the surgical team and require multidisciplinary review of cases to vet suitability for the robotic approach. Informed consent for R-RPLND must be especially thorough: patients are counselled that while nerve-sparing and quicker recovery are goals, there is a non-zero risk of conversion to open surgery and the primary aim is cancer cure. The selection process should remain dynamic, incorporating emerging evidence and individual patient values—for example, as new data on oncologic outcomes or quality of life arise, centres might broaden or narrow criteria accordingly. By continually refining selection in tumour board discussions, programs ensure that R-RPLND is offered to those most likely to benefit from it [47].

### Contraindications and limitations

There are clear situations where a R-RPLND is not recommended, and recognizing these upfront is critical to avoid compromising patient outcomes. Extensive post-chemotherapy fibrosis or desmoplastic reaction that obliterates tissue planes is a major contraindication, as the robotic tools have limited ability to feel through scar and establishing safe planes may be impossible. Similarly, tumour thrombus in the great vessels or bulky conglomerate nodes adherent to the aorta or vena cava often necessitate an open approach for safe vascular control. Large residual masses (for example > 8–10 cm) are generally handled open, as they may require manual blunt dissection and hand manoeuvres beyond robotic capability. If major vascular reconstruction (vena cava patch, aortic graft) is anticipated, an open operation is usually preferable given the need for quick haemostatic control. Patient factors also play a role: those with prohibitive cardiopulmonary issues might not tolerate prolonged pneumoperitoneum and steep positioning, making open surgery safer. Beyond anatomic factors, a lack of institutional experience or resources is a contraindication to attempt R-RPLND—a program without surgeons well-trained in RPLND, or without immediate availability of vascular surgery backup and appropriate critical care, should not embark on this complex robotic procedure. Importantly, surgeon judgment must remain paramount: if intra-operative findings exceed expectations (e.g. fibrosis far worse than pre-op imaging suggested), a low threshold for conversion to open is maintained. Case series consistently emphasize that strict selection and the willingness to abandon the robotic approach when needed are what prevent compromised oncologic outcomes [40]. In other words, trying to push ahead robotically in the wrong scenario can “normalize” undue risk and should be avoided. By adhering to well-defined contraindications and empowering surgeons to convert early, programs protect patient safety and maintain credibility of R-RPLND as a modality [40] (Table 2).

### Pre-operative work-up

Comprehensive pre-operative planning optimizes the chances of a smooth R-RPLND and oncologically effective surgery. Imaging is the cornerstone of planning: high-resolution contrast-enhanced CT (or MRI in select cases) of the abdomen and pelvis is used to map the location, size, and laterality of lymph node disease. This allows the surgical team to decide on the appropriate dissection template (left, right, bilateral) and anticipate any anatomical anomalies, such as a retroaortic left renal vein or variant inferior vena cava, that could impact the surgical approach. In post-chemotherapy cases, timing of surgery is typically scheduled about 4–8 weeks after completion of chemotherapy, once blood counts have recovered and any residual mass has declared itself on imaging. Tumour markers are rechecked to ensure they have normalized (for NSGCT) before proceeding, as persistent elevation might indicate the need for salvage chemotherapy instead of surgery. Anesthetic evaluation is important since R-RPLND often involves steep lateral positioning and can last several hours; patients are optimized for cardiopulmonary function and measures to prevent positional nerve injuries are planned. Mechanical bowel preparation is not universally required, but some centres use a minimal preparation to reduce bowel content and volume. On the morning of surgery, prophylactic measures

**Table 2** Pragmatic selection framework outlining scenarios in which a robotic approach is ideal or should generally be avoided for primary and post-chemotherapy R-RPLND based on current evidence and expert consensus

| Clinical scenario | Favourable features for R-RPLND | Features favouring open RPLND or alternative management |
|---|---|---|
| Primary R-RPLND for NSGCT (clinical stage I–IIA/B) | Unilateral, small-volume retroperitoneal disease on cross-sectional imaging (typically nodes ≤ 2–3 cm), normalised serum tumour markers after orchiectomy, absence of major vascular encasement, and a strong preference to avoid adjuvant chemotherapy. Procedure performed in a high-volume centre with established robotic and open RPLND expertise, where nerve-sparing templates are expected to be feasible | Bulky or multi-station nodal disease, radiologic concern for vascular invasion, need for en bloc visceral resection, significant cardiopulmonary comorbidity, or limited institutional experience with R-RPLND. In these settings, open RPLND or primary systemic therapy is usually preferred |
| Primary RPLND for seminoma (stage IIA/B) | Carefully staged low-volume nodal disease (typically ≤ 3 cm) with normal markers in patients prioritising a chemotherapy-sparing strategy, treated in centres with specific experience in surgical management of seminoma and robust multidisciplinary support | Bulky seminomatous disease, multifocal nodal involvement beyond a limited template, prior para-aortic radiotherapy, or lack of institutional experience. In such cases, standard systemic therapy or radiotherapy remains the default |
| Post-chemotherapy R-RPLND | Residual mass usually < 5–6 cm, peripherally located relative to the aorta and inferior vena cava, without radiologic evidence of major vessel thrombosis or circumferential encasement; patient has recovered from cisplatin-based chemotherapy and is fit for prolonged pneumoperitoneum. Case vetted in a high-volume centre with predefined thresholds for conversion | Very bulky residual masses (e.g. > 8–10 cm), confluent desmoplastic reaction obliterating tissue planes, tumour thrombus or clear invasion of great vessels, anticipated need for complex vascular reconstruction or multi-visceral resection, or absence of experienced robotic and vascular support. Open RPLND is preferred to maintain oncologic and technical safety |
| Salvage or repeat RPLND | Highly selected patients with small-volume, anatomically favourable relapse in whom prior surgery and imaging suggest that a nerve-sparing robotic dissection is technically achievable in an expert centre | Extensive re-operative retroperitoneal disease, dense adhesions from prior laparotomies, or scenarios in which rapid manual control of major bleeding may be required. In these contexts, an open salvage or desperation RPLND is recommended |

for deep vein thrombosis (compression devices, possibly low-dose heparin) are initiated given the long operative time. Planning also includes readiness for potential complications: blood products are cross-matched and immediately available, and instruments for open vascular control are kept in the room in case conversion is needed emergently. If the residual mass is adjacent to critical vessels like the renal artery or vena cava, vascular surgeons are notified to be on standby. Ureteral stents are sometimes pre-placed if the mass abuts the ureter heavily, to aid in intraoperative identification. Additionally, the patient is counselled about and offered sperm banking prior to surgery, given the small risk to fertility. In high-volume programs, a multidisciplinary tumour board review is standard—radiologists, medical oncologists, and surgeons confer on each case to agree that robotic surgery is appropriate and formulate contingency plans if unexpected findings arise. This thorough preparation has been shown to pay dividends. For example, institutions performing robotic PC-RPLND have reported smooth peri-operative courses due in part to careful pre-op imaging review and planning of manoeuvres, indicating that investing effort in the work-up phase directly contributes to surgical success [54, 55]. In sum, nothing in R-RPLND is “routine,” and a proactive strategy addressing patient factors, tumour anatomy, and resource availability is mandatory before making the first incision.

## Complications and safety profile

### Intra-operative complications

R-RPLND entails operating near major blood vessels and vital structures, so vigilant risk management is necessary throughout the case. The most significant intra-operative hazard is vascular injury, particularly tearing of lumbar veins or inadvertent laceration of the inferior vena cava or aorta. Fortunately, such events are uncommon in experienced hands. A multi-centre review of robotic post-chemotherapy RPLND reported a 6% incidence of any vascular injury, with only one case (1.5%) resulting in significant bleeding that prompted conversion to open surgery for repair [38]. This underscores that while minor venous tears may occur, they are often controlled robotically (with clips or sutures) and rarely progress to life-threatening haemorrhage if the team is prepared. Key to prevention is early control of vessels: surgeons routinely ligate or clip lumbar vessels and gonadal veins before dissecting bulky nodes, and they carefully skeletonize and encircle the great vessels when needed to gain proximal control. Another intra-operative issue is ureteral injury, but this is mitigated by visually identifying and mobilizing the ureter early in the dissection—to date, ureteral transections or loss of renal unit have not been widely reported in robotic series. Bowel injury is similarly rare due to the stable visualization and minimal bowel handling in the lateral approach. To handle crisis situations, the robotic team assigns specific roles in advance: for example, if major bleeding occurs, the bedside assistant is tasked with immediate pressure on the vessel with a swab or instrument while the console surgeon undocks to assist, and anesthesiology is alerted to be ready for hypotensive management or transfusion. Having a protocol for emergency conversion is crucial; this might include pre-positioning a small laparotomy incision site (e.g. marking a mini-midline) that can be rapidly opened if needed. Fortunately, in high-volume R-RPLND programs, most intra-operative complications that do occur are low-grade and can be corrected on the spot. The incidence of intra-operative complications appears similar or slightly lower than in open RPLND, given that robotic cases are carefully selected. Moreover, as surgeons climb the learning curve, the frequency of near-miss events tends to drop [30]. Ongoing data collection, including recording any "critical event" or aborted dissection, is important to continue improving safety. Overall, the evidence indicates that with proper precautions, R-RPLND can be performed with a low rate of serious intra-operative mishaps, and the capability to convert to open provides an additional safety net when needed.

### Post-operative complications

The post-operative recovery from R-RPLND is generally smooth, but certain complications characteristic of lymph node dissections can still occur and require prompt management. One well-known issue is chyle leak (lymphatic drainage into the retroperitoneum or through a surgical drain), resulting from disruption of lymphatic channels. In robotic cases, meticulous clipping of lymphatics and judicious use of surgical sealants have kept clinically significant chyle leaks relatively infrequent (often under 5–10% incidence). For example, a multi-centre series noted symptomatic lymphatic leakage in about 7–8% of patients, none of which required reoperation—most were managed conservatively with dietary modifications and, if needed, octreotide therapy [38]. Ileus is another complication to watch for, as bowel manipulation—albeit limited in robotic surgery—plus retroperitoneal inflammation can slow gastrointestinal recovery. Rates of ileus after R-RPLND are reported around 10% in recent cohorts [38]. Enhanced recovery protocols, including minimization of opioids, early oral intake, and ambulation on post-operative day one, have been effective in reducing ileus duration. Wound complications such as infection or hernia are very uncommon due to the small port incisions; however, extraction site hernias can occur rarely if a large specimen is removed, so these sites are typically closed carefully under direct vision. Lymphocele formation (a collection of lymph fluid in the retroperitoneum) can occur weeks after surgery, but the risk is minimized by the thorough ligation of lymphatics and occasionally leaving a drain in place for a few days post-op if extensive dissection was done. In contemporary robotic series, no patients have required re-intervention for lymphocele or abscess drainage, whereas these issues historically occurred in a small percentage of open cases. Importantly, no post-operative mortality has been reported in the R-RPLND literature, reflecting the young patient population and overall safety of the procedure. Large database analyses, such as a recent German national study (the "GRAND" study), are putting the R-RPLND complication profile in context by comparing it to open surgery benchmarks and identifying any factors that predispose to complications [56]. These big-data approaches help validate that complications like thromboembolism or pulmonary issues remain infrequent with robotics and guide improvements (for instance, emphasizing prophylaxis for deep vein thrombosis given patients' limited mobility immediately post-op). In summary, the post-operative course after R-RPLND is typically uneventful aside from the expected fatigue and mild ileus for a day or two. When complications do arise, they are usually manageable with conservative measures. The combination of minimally invasive technique and refined peri-operative care has yielded a low complication rate that compares favourably with historical open surgery outcomes [56].

### Nerve injury and ejaculatory function

Injury to the sympathetic nerves responsible for ejaculation is a unique concern in RPLND and can be considered both a "complication" and an expected side effect depending on the extent of dissection. The goal of R-RPLND is to avoid this complication through anatomical nerve-sparing whenever oncologically feasible. The sympathetic chain runs alongside the vertebral column, contributing fibres to the hypogastric plexus that govern emission of semen. In a right-sided dissection, for example, the ipsilateral post-ganglionic fibres can often be preserved by staying within the template boundaries and not crossing midline. In left-sided or bilateral dissections, nerve sacrifice is more likely if pathology dictates a full template. Robotic magnification aids tremendously in identifying these fine neural structures, which appear as white, glistening fibres that can be gently mobilized out of the dissection field. Still, if a tumour invades where these nerves reside, surgeons prioritize cancer control and may resect the nerves, resulting in retrograde ejaculation. Transparent pre-operative counselling prepares patients for this possibility, and sperm banking is advised in case fertility is later desired and ejaculation is impaired. The good news is that early robotic series are demonstrating excellent functional preservation. A single-centre study of primary R-RPLND reported that all evaluable patients maintained antegrade ejaculation post-operatively, attributing this success to strict unilateral templates and careful nerve-sparing technique [53]. Even in more challenging post-chemotherapy cases, over two-thirds of patients who had bilateral dissections still retained ejaculation in one report [48]. For those who do experience loss of ejaculation, referrals to fertility specialists are provided for discussion of assisted reproductive techniques if needed. It is also worth noting that patient-reported quality of life encompasses more than just a yes/no on ejaculation—some men adapt to changes with minimal distress, whereas others may have significant psychosocial impact. Long-term follow-up with standardized questionnaires (including sexual satisfaction scores) is therefore recommended. In terms of motor or sensory nerve injury (e.g., femoral neuropathy from retractor pressure in open surgery), this is virtually unheard of in robotic cases due to the lack of prolonged retraction. Overall, R-RPLND has proven that, in experienced hands, it can achieve cancer control while preserving ejaculatory function in the majority of cases [53]. By continuing to refine nerve-sparing approaches and candidly discussing outcomes, surgeons ensure that patients have realistic expectations and the best possible quality of life after surgery.

## Future perspectives and emerging technologies

### Advancements in robotic technology

The field of robotic surgery is continually evolving, and upcoming innovations hold promise to further improve R-RPLND. Current third- and fourth-generation surgical robots offer greater degrees of freedom, better instrument precision, and integrated adjuncts that were not available in earlier RPLND experiences. For instance, the newest platforms have refined energy devices and staplers that can be used robotically, potentially streamlining vessel control and specimen division. Tactile feedback remains a limitation of robotic systems, but research into haptic feedback or alternative sensory cues may eventually help surgeons perceive resistance or tissue texture remotely, enhancing safety during delicate manoeuvres around vessels. Another area of improvement is robotic instrumentation specifically designed for lymphadenectomy—longer instruments or flexible suction devices could help reach deep paracaval or retrocrural areas without repeated repositioning. Efficiency gains are also anticipated: as docking mechanisms become smoother and user-friendly, setup times will decrease, allowing surgeons to focus more on dissection and less on equipment. The impact of these advancements is evident in the progressive reduction of operative times and conversions in high-volume centres over the years [13]. Each incremental improvement, be it a faster processor for the robotic arms or an improved camera lens with wider field, translates to a more controlled and expeditious surgery. Importantly, all new technology should undergo rigorous evaluation to ensure it indeed benefits the patient. Metrics such as total operative time, blood loss, complication rates, and functional outcomes will continue to be collected and stratified by generation of robot used. If, for example, a new robotic arm design allows easier suturing of the vena cava, one would expect to see even fewer conversions for vascular repair. The future likely holds multiple competing robotic platforms as well, which could drive innovation and reduce costs. From the surgeon's perspective, standardization of technique leveraging these technologies will be key—the robot is a tool, and how it's used matters. We anticipate that as technology advances, R-RPLND will become increasingly accessible and reproducible, allowing more centres to adopt the procedure safely. However, maintaining oncologic rigor is paramount: any new gadget or system must be integrated in a way that does not detract from cancer control. In summary, ongoing robotic innovations will enhance the surgeon's capabilities, but careful measurement and validation (as early pioneers of R-RPLND have emphasized) will guide which advances truly improve patient outcomes [13].

### Image-guided surgery and augmented reality

One exciting frontier for R-RPLND is the incorporation of advanced imaging techniques into the intra-operative environment. Augmented reality (AR) overlays could superimpose preoperative imaging (CT or MRI) onto the surgeon's console view, helping to localize deep nodal packets or aberrant vessels that are not immediately visible. In the complex retroperitoneal landscape, such guidance might reduce uncertainty—for example, highlighting the exact location of a left renal artery in relation to a mass, or delineating the cephalad extent of a template near the renal vessels. Pilot studies are exploring the registration of 3D imaging to the patient in real time, but challenges remain in ensuring perfect alignment and accounting for organ shift once insufflation occurs. Another adjunct is the use of near-infrared fluorescence. Administering indocyanine green (ICG) dye can help identify lymphatic channels (they fluoresce under near-infrared light) or confirm perfusion of organs like kidneys after a lengthy dissection. Some groups have also used fluorescence ureteral stents which make the ureter glow on camera, virtually eliminating any risk of accidental ureteral injury. The lateral single-docking approach of R-RPLND is particularly amenable to integrating these technologies, since the camera can maintain a steady perspective for AR overlays without need for frequent reorientation. Early experiences have shown that these tools are feasible—for instance, fluorescence mapping has identified thoracic duct or lymphatic lakes that were then clipped to prevent chyle leak [45]. The next step is formal evaluation: clinical trials or prospective series are needed to quantify whether image guidance shortens operative time, reduces complications, or improves completeness of dissection. Surgeons must also be trained to use the technology without distraction; teams often rehearse with the AR software to understand its quirks (such as slight delays in overlay projection or calibration drift). As these digital aids improve, one can envision a future R-RPLND where the surgeon sees a coloured map of risk zones (like where nerves are likely, or tumour boundaries) in their console, much like a heads-up display. Ultimately, the goal of image-guided robotic surgery is to enhance the surgeon's situational awareness, making an already precise operation even more targeted. Within the next decade, as pioneering single-surgeon series and technical papers continue to lay the groundwork [45], we expect image-guided R-RPLND to transition from experimental to a standard component of high-complexity cases.

### Clinical trials, training, and adoption

For R-RPLND to solidify its role in testicular cancer, broader validation and dissemination are required through clinical trials and collaborative studies. A number of prospective trials are underway or in development—these aim to compare oncologic outcomes of robotic versus open RPLND, assess quality of life differences, and refine selection criteria. While randomized controlled trials in this space are challenging (given strong surgeon and patient preferences), registry-based comparative studies can provide high-level evidence. International collaborations, such as multi-centre databases or consensus statements, will help pool the relatively limited volume from individual centres to draw more powerful conclusions about long-term cancer control. In parallel, the training pipeline for robotic urologic oncologists is evolving. High-volume centres have initiated fellowship programs emphasizing RPLND technique, and virtual telementoring is increasingly used to help mentor surgeons in remote locations. Simulation-based training modules for R-RPLND are also being developed, allowing surgeons to practice the procedural steps on virtual reality platforms or cadaveric models before performing on patients. This structured approach to training is essential to maintain outcomes as adoption widens. Not every hospital should offer R-RPLND; instead, regional referral centres of excellence are emerging, concentrating experience and providing mentorship to surrounding providers. The Swedish-Norwegian national program is an illustrative example, where all robotic RPLNDs are funnelled to a single high-volume centre—their population-based data showed that roughly one-third of all RPLND candidates could be managed robotically with excellent results, while the rest underwent open surgery due to more advanced disease [41]. Such centralization ensures that robotic cases are done by truly experienced teams and that open surgery expertise is still readily available for those who need it. It also facilitates transparent reporting of outcomes; many programs now maintain prospective databases tracking oncologic and functional results, which are periodically published or presented. By openly sharing both successes and complications, the field can calibrate its expectations and improve patient selection algorithms. In the coming years, widespread adoption of R-RPLND will depend on demonstrating its value proposition in terms of patient-centric outcomes (faster recovery, preserved fertility) without sacrificing cure rates. If ongoing trials and registries confirm these benefits, we can expect guidelines to formally incorporate R-RPLND as an acceptable approach in specific scenarios. Ultimately, the future vision is a network of centres where young men with testicular cancer have access to a full range of treatment options—including state-of-the-art robotic surgery—delivered by teams who are well-trained, quality-monitored, and focused on multidisciplinary care. This model will ensure that R-RPLND is used judiciously and continues to innovate in parallel with advances in oncology and technology. Where comparative figures (robot vs open) are cited without confidence intervals or pvalues, they should be interpreted as descriptive rather than inferential [57].

## Limitations and risk of bias in the literature

The synthesis of the available literature on Robot-Assisted Retroperitoneal Lymph Node Dissection (R-RPLND) is subject to several important limitations and potential sources of bias that must be considered when interpreting the findings. A primary concern is the pervasive selection bias evident across most nonrandomized series; there is a clear tendency to select patients with more favourable disease characteristics for the robotic approach, particularly in early single-centre experiences and in post-chemotherapy cohorts, which may artificially inflate the apparent safety and efficacy of the procedure. Compounding this are significant learning-curve effects, as perioperative outcomes demonstrably improve over time as surgical teams gain experience, meaning that results from mature programs may not be generalizable to centres in the earlier stages of adoption. Furthermore, the majority of comparative studies are limited by confounding variables—such as differences in tumour stage, the extent of the dissection template, and adjunctive procedures—that are not adequately adjusted for, which restricts the ability to make causal inferences when comparing robotic versus open approaches. The literature is also marked by substantial heterogeneity in both surgical techniques (e.g., modified unilateral vs full bilateral templates) and clinical indications (primary vs post-chemotherapy), a factor that precludes the direct quantitative pooling of many endpoints and necessitates a more narrative synthesis. Data collection itself presents challenges, with inconsistent reporting of follow-up durations and a frequent lack of standardized, patient-reported outcomes for key metrics like ejaculatory function, often requiring reliance on median values and qualitative descriptions. Finally, the evidence base is likely influenced by both publication bias, which favours the reporting of favourable robotic outcomes, and centre selection bias, as patients are preferentially referred to high-volume centres, whose excellent results may not be representative of wider clinical practice. These factors collectively temper the strength of comparative statements and underscore the need for cautious interpretation of the currently available data.

## Conclusions and expert perspectives

Based on the available evidence, robot-assisted retroperitoneal lymph node dissection (R-RPLND) appears to be a safe and feasible minimally invasive alternative to open RPLND for carefully selected patients with testicular germ-cell tumours, particularly when undertaken by experienced teams in high-volume referral centres. Across retrospective single- and multicentre series, R-RPLND is consistently associated with lower estimated blood loss, shorter hospital stay, and faster recovery than open surgery, while achieving broadly similar nodal yields and low rates of in-field retroperitoneal recurrence in primary and selected post-chemotherapy settings; however, these observations derive from non-randomised cohorts with substantial selection and centre bias and should be interpreted as descriptive rather than definitive evidence of superiority. Enhanced magnified visualisation facilitates meticulous nerve-sparing dissection and has translated into high rates of preserved antegrade ejaculation in most primary R-RPLND cohorts, supporting its role within fertility-preserving pathways. For men with clinical stage I–IIA/B non-seminomatous germ-cell tumours, primary R-RPLND can provide definitive pathological staging and cure for a substantial proportion, enabling chemotherapy-sparing strategies in appropriately counselled patients; emerging data also support a carefully selected role for RPLND in low-volume metastatic seminoma as a means of avoiding or deferring systemic therapy. By contrast, post-chemotherapy R-RPLND remains technically demanding, with higher rates of complications and conversion to open surgery; here, strict selection based on tumour size, location, vascular and fibrosis burden, and a low threshold for early conversion are crucial, and open RPLND should remain the default for bulky, centrally located, or vascularly encased residual masses. Overall, current evidence supports the incorporation of R-RPLND into modern testicular cancer pathways as one option for primary and selected post-chemotherapy disease in expert centres, while recognising that the literature is dominated by retrospective series, learning-curve effects, and limited long-term follow-up. Prospective registries and, where feasible, comparative trials are needed to confirm durable oncologic equivalence, refine selection criteria, and optimise training and centralisation models.

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## Declarations

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