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Function-preserving strategies for localized prostate cancer: minimally invasive radical surgery, focal therapy and AI-assisted surgery

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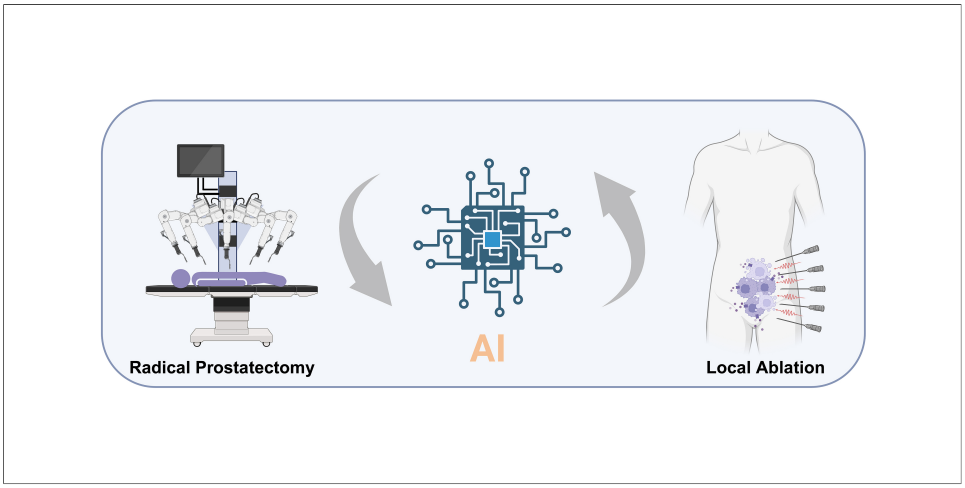

Abstract

With increasing detection and longer survival in localized prostate cancer (PCa), treatment goals increasingly emphasize preserving urinary continence and sexual function without compromising oncological control. This review synthesizes evidence on function-preserving strategies, focusing on minimally invasive radical prostatectomy, focal ablation, and artificial intelligence (AI)-assisted surgery. Laparoscopic and robot-assisted radical prostatectomy remain the principal radical approaches; multiport robot-assisted surgery has the most mature evidence for balancing cancer control and functional recovery. Relevant refinements include nerve-sparing, fluorescence imaging, three-dimensional reconstruction, and AI-assisted risk stratification, planning, navigation, and outcome prediction. In carefully selected patients with low- or intermediate-risk disease, focal therapies may reduce treatment burden and preserve function. Focal therapy is not yet a

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standard option for localized prostate cancer, but it may be discussed during shared decision-making with carefully selected, fully informed patients. Some focal modalities are already used in selected clinical settings, including outside formal trials where locally permitted, although implementation varies across health-care systems. Counseling should address limitations in long-term evidence, the need for structured surveillance, and possible repeat or salvage treatment. Heterogeneous selection, endpoints, and follow-up, together with a lack of high-quality head-to-head comparisons, preclude reliable ranking of focal modalities; sexual recovery and long-term oncological durability also vary. Direct evidence that AI improves nerve preservation, continence, erectile function, or margin control remains insufficient for routine adoption. Optimal function preservation requires risk-adapted selection, technical expertise, multidisciplinary decision-making, and rigorous follow-up. Future studies should prospectively validate AI tools and standardize imaging, outcomes, and clinically meaningful endpoints.

INTRODUCTION

Prostate cancer is one of the most common malignancies in men. The Global Cancer Observatory (GLOBOCAN) 2022 estimated approximately 1.47 million new cases worldwide, accounting for 7.3% of all newly diagnosed cancers[1]. For patients with a relatively long life expectancy who are suitable for local curative treatment, radical prostatectomy (RP) remains one of the most important curative options for localized prostate cancer. The European Association of Urology (EAU) guidelines state that RP should be actively considered for patients with a life expectancy of more than 10 years who are candidates for local treatment, and that the decision to perform nerve-sparing surgery should be based on the risk of extracapsular extension[2]. The 29-year follow-up of the Scandinavian Prostate Cancer Group Study Number 4 (SPCG-4) randomized controlled trial further showed that, compared with watchful waiting, RP reduces prostate cancer-specific mortality and the risk of metastasis, and provides long-term survival benefit in patients with longer life expectancy[3].

With earlier diagnosis and longer overall survival (OS), the goals of surgical treatment for prostate cancer are no longer confined to tumor removal alone but increasingly emphasize maximizing preservation of urinary continence and sexual function while maintaining oncological control. Urinary incontinence and erectile dysfunction are the major factors affecting postoperative quality of life and treatment acceptance, and meticulous preservation of the neurovascular bundles (NVBs), urethral sphincter, and anterior supportive structures of the prostate is crucial to reducing these complications[4]. In this context, minimally invasive radical surgery characterized by nerve-sparing techniques, precise dissection and tissue reconstruction - particularly laparoscopic radical prostatectomy (LRP) and robot-assisted radical prostatectomy (RARP) - has emerged as a key direction in the development of function-preserving treatments for prostate cancer.

This review therefore frames function-preserving treatment as a risk-adapted continuum rather than as a binary comparison between radical surgery and focal therapy. For RP, the central clinical question is how surgical access, nerve-sparing strategy, real-time imaging, three-dimensional (3D) reconstruction, and adjunctive decision-support tools can be combined to preserve urinary and sexual function without compromising margin control. For focal therapy, the key issue is not merely technical feasibility, but whether lesion selection, treatment extent, retreatment strategy, and surveillance can be standardized sufficiently to justify a function-preserving approach in carefully selected patients.

Recent reviews have separately summarized artificial intelligence (AI) in RARP and the use of 3D models or augmented reality (AR) in RP[5-7]. Given the growing relevance of AI to robotic surgery and urology, this review examines AI-specific applications across the perioperative pathway, including preoperative risk stratification, image segmentation, treatment decision support, intraoperative navigation, outcome prediction, data standardization, model validation, regulatory considerations, and barriers to clinical

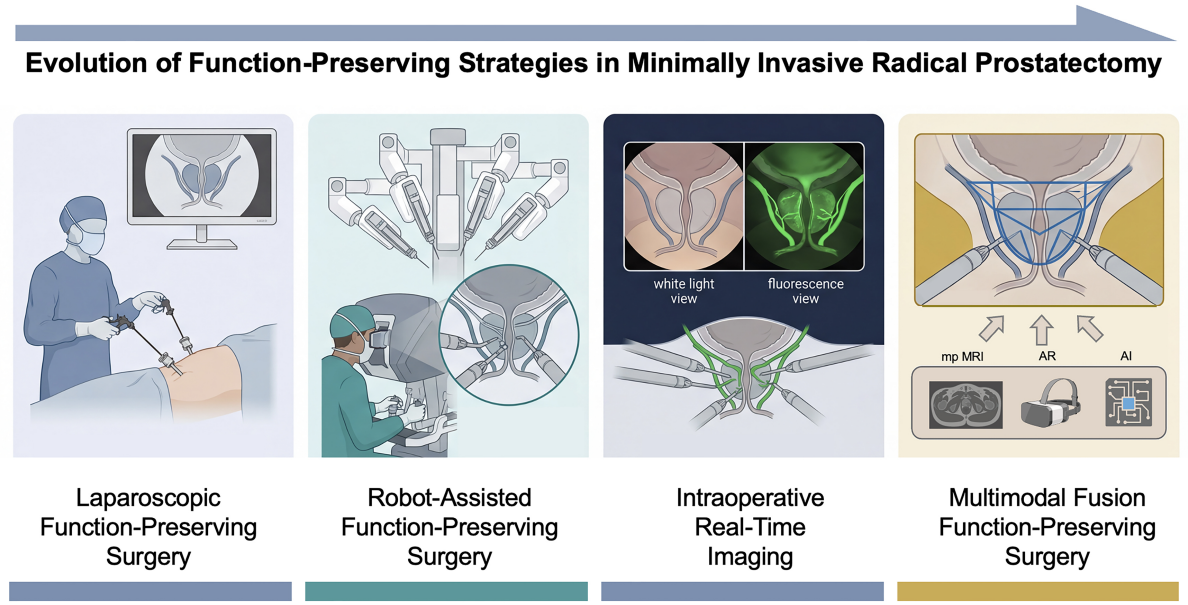

Figure 1. Evolution of function-preserving strategies in minimally invasive radical prostatectomy.

implementation. By integrating surgical anatomy, functional outcomes, focal ablation evidence, and AI-enabled decision support, this endpoint-centered synthesis distinguishes evidence directly related to continence, erectile function, nerve preservation, and positive surgical margins from indirect diagnostic, prognostic, and advanced-disease evidence.

FUNCTION-PRESERVING RADICAL PROSTATECTOMY FOR PROSTATE CANCER

Improved understanding of prostatic anatomy and advances in minimally invasive techniques have made preservation of the NVBs and supporting anatomical structures a key strategy for improving postoperative sexual function and urinary control. Currently, LRP and RARP constitute the main technical pathways for function-preserving radical surgery. In addition, multimodal data integration provides further opportunities for procedural refinement. Figure 1 illustrates the development of minimally invasive RP for prostate cancer.

Laparoscopic function-preserving surgery

LRP represents an important stage in the development of minimally invasive surgery for prostate cancer and serves as an important reference for understanding the subsequent advantages of robotic platforms. Its main limitations include a two-dimensional operative view, restricted instrument freedom, and a prolonged learning curve for complex suturing, all of which directly affect the consistency of nerve sparing, urethral reconstruction, and functional recovery.

The broader evidence comparing robotic and open RP also supports a cautious functional advantage for RARP. A 2026 systematic review and meta-analysis of 27 prospective comparative studies involving 38,530 patients associated RARP with less blood loss, fewer transfusions and overall complications, shorter hospitalization, and better early continence and erectile-function recovery than open RP; however, heterogeneity was substantial for several outcomes, and additional randomized trials with longer follow-up remain necessary[8]. For LRP *vs.* RARP, high-quality direct comparative evidence comes from the LAP-01 randomized, patient-blinded, multicenter trial and its 12-month follow-up. In this trial of 782 patients, RARP

was associated with a higher continence recovery rate than LRP at 3 months (54% *vs.* 46%), whereas the between-group difference attenuated and was no longer statistically significant at 12 months[9,10]. These findings suggest that LRP can achieve function preservation, but its recovery trajectory may depend more heavily on surgeon experience and may be less favorable than RARP with respect to early continence recovery.

A similar pattern is observed for sexual function recovery. A 2025 systematic review and meta-analysis including 13 studies and 6,281 patients showed that RARP was associated with better erectile function recovery than LRP at 3, 6, and 12 months after surgery, with a 12-month risk difference of 0.06 [95% confidence interval (CI), 0.02-0.10][11]. Thus, LRP retains an important place in the evolution of minimally invasive prostate cancer surgery; however, when the primary goals are nerve preservation and accelerated functional recovery, robotic platforms may offer advantages in early recovery.

Robot-assisted function-preserving surgery: multiport and single-port platforms

Multiport robot-assisted radical prostatectomy (MP-RARP) remains the minimally invasive approach supported by the most mature body of evidence and serves as the principal reference platform when discussing nerve-sparing surgery. Its advantages lie not only in 3D high-definition visualization and wristed instruments, but also in the resulting ability to identify anatomical planes more consistently, control traction and thermal injury, and perform more refined urethral reconstruction. Although anterior, lateral, and posterior approaches differ in specific operative steps, they share the same objective: to achieve a better balance between oncological control and function preservation.

On this platform, postoperative functional outcomes appear to depend less on the use of a robot per se than on the specific mode of nerve preservation and tissue handling. Guimarães *et al.* reported that anterior periprostatic tissue preservation and a clipless technique were associated with shorter mean time to continence recovery (5.8 months *vs.* 6.6 months) and a higher 12-month erectile function recovery rate (75.0% *vs.* 53.5%)[12]. Görgen *et al.* further showed that patients with higher NVB preservation scores had a 12-month trifecta rate of 66.6%, compared with 33.3% in the lower-score group[13]. However, nerve sparing is an independent risk factor for ipsilateral positive surgical margins [odds ratio (OR) 1.42][14]. The value of MP-RARP also lies in the development of intraoperative decision-making systems such as the neurovascular structure-adjacent frozen-section examination (NeuroSAFE). The NeuroSAFE PROOF trial demonstrated that NeuroSAFE-guided RARP improved 12-month erectile function [mean International Index of Erectile Function-5 (IIEF-5): 12.7 *vs.* 9.7] and short-term urinary continence at 3 months[15]. A 2025 systematic review and meta-analysis (4,207 patients) associated NeuroSAFE with higher nerve-sparing rates (OR 5.49), lower positive margins (OR 0.55), lower biochemical recurrence (OR 0.47), and better 12-month functional recovery (ORs 2.01 and 3.50)[16]. Nevertheless, due to the predominance of nonrandomized studies and limited long-term follow-up, these findings remain supportive rather than definitive.

Single-port robot-assisted radical prostatectomy (SP-RARP) can be understood as an optimization of the surgical access route within existing RARP principles rather than a redefinition of nerve preservation. Its main advantages lie in fewer incisions, better postoperative pain control, and shorter hospital stay. A 2025 updated meta-analysis (15 studies, 3,116 patients) found that SP-RARP was associated with lower estimated blood loss, shorter hospital stays, earlier catheter removal, lower pain scores, and less opioid use, whereas continence, potency, complications, positive margins, biochemical recurrence, and operative time did not differ significantly from MP-RARP[17]. A recent propensity-matched comparison [285 single-port (SP) transvesical *vs.* 285 multiport (MP) transperitoneal] reported higher same-day discharge rates, shorter catheterization duration, less opioid prescribing, and better 3-month continence with the SP approach, whereas 6-month continence, 12-month potency, and oncological outcomes were similar; however, the study

was retrospective and single-center[18]. Thus, the most prudent current conclusion is not that SP-RARP has surpassed MP-RARP in long-term outcomes, but rather that SP approaches may improve selected perioperative recovery metrics and possibly early continence in experienced settings without compromising short- to mid-term cancer control. The technical characteristics and reported outcomes of the different approaches are shown in Table 1.

Intraoperative fluorescence imaging-assisted function-preserving surgery

If refinements of robotic dissection focus on how tissue is handled, intraoperative fluorescence imaging addresses how key structures can be visualized in real time. The most widely studied strategy in RP uses intravenous indocyanine green (ICG) with near-infrared fluorescence (NIRF) integrated into the robotic platform to enhance visualization of periprostatic vessels, the landmark artery within the NVB, and local perfusion. In principle, this may help the surgeon identify safer dissection planes, limit unnecessary traction or cautery near the NVB, and improve hemostasis, thereby supporting postoperative functional recovery. At present, however, the evidence base remains limited and is derived mainly from feasibility and early clinical studies rather than randomized comparative trials.

In the initial clinical experience reported by Mangano *et al.*, indocyanine green-near-infrared fluorescence (ICG-NIRF) was used during nerve-sparing RARP to identify the landmark artery and facilitate preservation of the NVB, demonstrating technical feasibility and satisfactory intraoperative visualization[27]. More recently, Amara *et al.* analyzed 91 consecutive patients with localized prostate cancer who underwent ICG-NIRF-guided RARP and reported successful NVB identification in all cases, no ICG-related complications, and no significant difference between baseline and 9-month Sexual Health Inventory for Men (SHIM) scores (P = 0.331), with erectile function returning to baseline in most patients[28]. These findings suggest that fluorescence guidance may be a useful adjunct for real-time microanatomical dissection. Nevertheless, because current studies are mostly retrospective, non-comparative, and focused on short-term feasibility, intraoperative fluorescence imaging should presently be regarded as a promising supportive tool rather than an established standard for function preservation.

Multimodal fusion function-preserving surgery

While fluorescence imaging improves what can be seen intraoperatively, multimodal data fusion and 3D reconstruction seek to improve what can be understood before and during surgery. In current practice, preoperative multiparametric magnetic resonance imaging (mpMRI) remains the core imaging substrate, but image-derived information can also be integrated with biopsy, clinical, and perioperative variables to support both anatomical navigation and side-specific risk assessment. By segmenting the prostate, index lesion, capsule, urethra, and adjacent NVBs from preoperative imaging into patient-specific 3D models, surgeons can translate tumor location and extracapsular extension risk into a more intuitive operative map. When these models are used for cognitive review or overlaid onto the robotic console as AR, the goal is not to replace intraoperative judgment, but to make nerve-sparing decisions more individualized and anatomically explicit.

Schiavina *et al.* overlaid preoperative augmented-reality 3D models onto the intraoperative field in 26 RARP cases and found that the nerve-sparing plan changed in 38.5% of patients and 34.6% of sides, with overall system applicability of 94.4%; on a 32-region map, lesion-localization sensitivity, specificity, and accuracy were 70%, 100%, and 92%, respectively[29]. In a later randomized clinical trial secondary analysis including 92 patients, Shirk *et al.* reported that use of 3D digital models for planning robotic prostatectomy was associated with lower 18-month biochemical recurrence (0% *vs.* 17.9%), less adjuvant or salvage radiotherapy (3.1% *vs.* 31.6%), better sexual function (mean SHIM score 16.8 *vs.* 9.8), and a higher trifecta rate (48.0% *vs.* 10.0%), while continence was similar between groups[30].

Table 1. Classification-based comparison of the main RARP access routes and the SP platform for function-preserving radical prostatectomy

Approach	Initial entry site	Key anatomical plane	Reported clinical contexts	Complications and functional highlights	Oncological expectations
Anterior (TP)	Enter the Retzius space first through an anterior peritoneal incision	Early exposure of the endopelvic fascia, puboprostatic/pubovesical ligaments, DVC, bladder neck, and then the posterior plane	Most familiar route for routine localized disease and for surgeons trained in open anatomy; facilitates standard PLND	Provides the largest working space. Hood-type anterior preservation reported continence of 21%, 36%, 83%, 88%, and 91% at 1, 2, 4, 6, and 12 weeks, with a 6% PSM rate in a single-center series[19]	Mature oncological experience; functional recovery depends heavily on how much anterior/periurethral support is preserved and on tumor location[20]
Posterior RS (Bocciardi, TP)	Posterior entry via the pouch of Douglas, exposing the vas deferens and seminal vesicles first	Posterior intrafascial dissection between Denonvilliers' fascia and the rectum; preserves the puboprostatic/pubovesical complex and usually avoids DVC ligation	Reported in settings where early continence recovery is prioritized; requires experienced surgeons and careful anatomical and oncological selection	The main advantage is faster continence recovery. In a randomized study, immediate continence was 51% *vs.* 21%, with median recovery of 1 day *vs.* 21 days; meta-analyses confirm the early continence benefit[21,22]	Short- to mid-term cancer control is generally comparable, but margin caution is warranted in selected anterior or ≥ pT3 disease[21,22]
Lateral (TP)	A lateral "buttonhole" is created through the bladder neck-prostate-vascular pedicle/NVB triangle	Posterolateral structures and the NVB are addressed first, while the anterior pubovesical complex is preserved as much as possible	Selected localized cases in which extensive NVB preservation is considered; requires familiarity with posterolateral hemostasis	In a 513-patient series, immediate continence was 85%-86% and 1-year potency 72%-73%[23]	PSM was 32.9%-37.9%, whereas clinically significant margins were 5.9%-7.6%; evidence is mainly retrospective and from high-volume centers[23]
VIP (TP)	Anterior transperitoneal access on the robotic platform	Progressive preservation of lateral/posterolateral fascial tissue; veil and super-veil refinements extend anterior fascial and nerve preservation	Used when continence and potency preservation is strongly emphasized in organ-confined disease; requires a highly experienced team	The 2009 VIP technical update formalized superveil nerve sparing and other refinements to improve trifecta-oriented recovery while maintaining the minimally invasive benefits of robotic surgery[24]	Feasible with good cancer control in expert hands, but technical complexity has limited broad dissemination[24]
Extraperitoneal	The working space is created outside the peritoneal cavity without entering the abdomen	Standard prostate dissection is completed within the preperitoneal space	Useful when minimizing bowel manipulation is desirable, including in patients with prior abdominal surgery or concern for postoperative ileus	A meta-analysis of 16 studies (3,897 patients) showed faster operative time, shorter stay, and lower postoperative ileus and inguinal hernia rates than transperitoneal RARP[25]	Positive margins and 6-month continence were similar to transperitoneal RARP[25]
Transvesical (mainly SP)	Direct entry through the bladder dome, with the prostate approached from within the bladder	Regionalized intravesical dissection limits disturbance of the anterior Retzius structures	Reported as an option for patients with hostile abdomens or prior abdominal surgery, and in settings emphasizing rapid recovery and short catheterization	In a matched comparison, SP transvesical RARP achieved 47% immediate continence and 82.8% continence at 3 months, with shorter catheterization (4 days *vs.* 7 days) and markedly less opioid prescribing[18]	Short- to mid-term oncological outcomes were similar to standard MP transperitoneal RARP in experienced centers[18]

Perineal route	Perineal access directly beneath the prostate, avoiding the peritoneal cavity	Dissection is performed through the perineal route with limited pelvic working space	May be considered in selected patients with complex abdominal surgical history or frozen pelvis, when abdominal access is problematic	Offers a scar-sparing nonabdominal route, but comparative evidence remains limited and the procedure is technically demanding[26]	In a matched study of SP radical perineal prostatectomy, nonlimited PSMs were higher than with MP transperitoneal RARP, although 1-year biochemical recurrence was similar[26]
SP platform	Single skin incision using the purpose-built SP robotic platform; can be deployed transperitoneally, extraperitoneally, transvesically, or transperineally	"Regionalized" access with multi-jointed instruments and fewer abdominal wall punctures	Use has mainly been reported in centers with platform-specific experience when smaller access trauma and accelerated discharge are priorities	An updated meta-analysis showed less blood loss, shorter hospital stay, earlier catheter removal, and lower pain/opioid use than MP-RARP, while continence and potency were broadly similar overall[17]	Short- to mid-term oncological outcomes appear comparable to MP-RARP, but long-term and approach-specific evidence remains less mature[17,18]

This table is organized by access route/platform rather than by a single anatomical dissection plane. Because definitions of continence, potency, and margin assessment vary across studies, the reported outcomes are intended as descriptive evidence rather than a direct ranking of superiority. RARP: Robot-assisted radical prostatectomy; TP: transperitoneal; VIP: Vattikuti Institute prostatectomy; SP: single-port; MP: multiport; RS: Retzius-sparing; DVC: dorsal venous complex; NVB: neurovascular bundle; PLND: pelvic lymph node dissection; PSM: positive surgical margin.

The prospective multicenter RIDERS randomized trial provides more direct evidence. Among 133 patients with extracapsular extension or bulging on preoperative magnetic resonance imaging (MRI) who underwent nerve-sparing RARP, 3D-AI-AR guidance was associated with a lower overall positive surgical margin (PSM) rate (22% *vs.* 39%), less postoperative radiotherapy (18% *vs.* 35%), and higher 12-month zero-pad continence (91% *vs.* 71%) than cognitive MRI guidance, while potency and short-term biochemical recurrence were similar[31]. These results are encouraging, but they arise from a selected population and 12 months of follow-up; longer-term oncological assessment and external replication are required before routine implementation.

FUNCTION-PRESERVING FOCAL ABLATION FOR PROSTATE CANCER

Current evidence suggests that focal ablation may be most appropriate for carefully selected patients with low- to intermediate-risk disease in whom lesions can be adequately delineated by imaging and targeted biopsy. Focal therapy is not yet a standard option, but it may be discussed during shared decision-making with carefully selected, fully informed patients[32]. EAU guidance places particular emphasis on prospective evidence generation, with registry-based recommendations for high-intensity focused ultrasound (HIFU) or cryotherapy and trial-based recommendations for other ablative modalities[2]. These recommendations coexist with current clinical practice: some focal modalities are already used in selected clinical settings, including outside formal trials where locally permitted, although their availability and pathways for implementation vary by jurisdiction. Accordingly, the evaluation of focal therapy in this review is framed around functional benefit, patient selection, surveillance, and the maturity of oncological evidence, rather than as evidence of equivalence to established curative standards. Figure 2 illustrates currently common focal ablation techniques and their underlying principles.

Cryotherapy

Cryotherapy induces tissue necrosis through intracellular ice crystal formation, membrane disruption, and microvascular thrombosis caused by low temperature. Its major advantage is that the ablation boundary can be monitored under ultrasound guidance, while temperature probes can help protect the urethra and rectum. Its principal appeal in focal therapy therefore lies in perioperative safety and the potential for function preservation; long-term oncological durability has not been conclusively established. An early systematic review reported post-focal cryotherapy continence rates of 96%-100%, urinary retention rates of 0%-15%, and a very low rate of rectourethral fistula, while erectile dysfunction ranged widely from 0% to 42%[33].

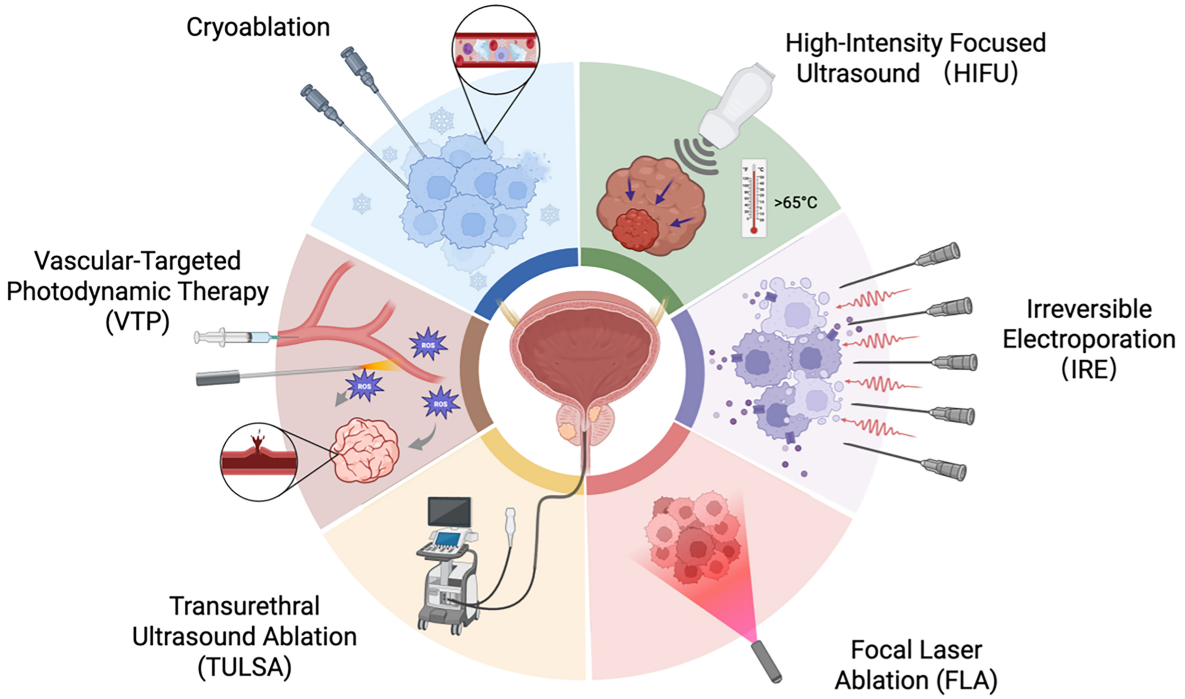

Figure 2. Schematic illustration of the major focal ablation techniques for prostate cancer and their mechanisms of action. [Created in BioRender. Zhang, C. H. (2026) https://BioRender.com/hda0tdq]. VTP: Vascular-targeted photodynamic therapy; TULSA: transurethral ultrasound ablation; FLA: focal laser ablation; IRE: irreversible electroporation; HIFU: high-intensity focused ultrasound.

Because of its relatively low perioperative morbidity, cryotherapy has long been considered a tissue-preserving option for carefully selected patients. However, its key limitation lies not in short-term safety but in the continued insufficiency of long-term oncological evidence. In the studies included in the cited systematic review, the positive follow-up biopsy rate was 21.8%[33]. Cryotherapy may therefore be considered a function-preserving option in selected patients, but current evidence does not establish equivalence to RP or radiotherapy.

HIFU

HIFU uses focused ultrasound to generate high temperature within the target zone, leading to protein coagulation and cell death, and is one of the most widely applied focal therapies with a relatively substantial evidence base. Thus, the assessment of HIFU should not center solely on theoretical feasibility, but on whether it appears to have developed relatively stable mid-term oncological control and functional outcomes. In a multicenter prospective cohort reported by Guillaumier *et al.*, 625 patients with clinically significant, nonmetastatic prostate cancer were included; the 5-year failure-free survival (FFS) was 88%, metastasis-free survival (MFS) 98%, cancer-specific survival (CSS) 100%, and OS 99%. Among patients completing questionnaires, 241/247 (98%) maintained complete pad-free continence, and only 2% used any pads[34].

However, the outcomes of HIFU are still clearly influenced by case selection and treatment extent. A 2024 systematic review of whole-gland HIFU that included 6,618 patients reported biochemical disease-free survival rates ranging from 21.7% to 89.2% and negative biopsy rates ranging from 20% to 92.7%, indicating substantial inter-center variability[35]. These whole-gland results cannot be directly extrapolated to focal HIFU. Overall, HIFU may currently be regarded as one of the focal ablative modalities supported by a relatively more substantial evidence base, but its clinical use still depends on strict patient selection and standardized follow-up.

Irreversible electroporation

Irreversible electroporation (IRE) is a nonthermal ablation technique that induces apoptosis by creating irreversible nanopores in the cell membrane through high-voltage pulses. Because it causes relatively limited damage to collagen scaffolds and surrounding heat-sensitive structures, IRE is theoretically well suited to preserving the urethra, sphincter, and NVBs; accordingly, its most closely watched advantage relates to functional preservation.

Available clinical data largely revolve around this point. The prospective Targeted Ablation Using Ultrasound-Guided Irreversible Electroporation of Index Tumors (TARGET) study enrolled 20 intermediate-risk patients, 19 of whom completed treatment. At 6 months, urinary and sexual function scores showed no clear decline; at 12 months, 14/19 (74%) patients had no clinically significant cancer detected throughout the whole gland; and the 2- and 4-year rates of freedom from radical treatment were 79% and 73%, respectively[36]. In addition, in a long-term cohort of 229 patients reported by Scheltema *et al.*, the median follow-up was 60 months, the 5-year FFS was 84%, MFS was 99.6%, and both CSS and OS were 100%; continence at 12 months was maintained from 98% at baseline to 99%, but erections sufficient for intercourse declined from 71% to 58%[37].

More recently, the prospective, nonrandomized, multicenter PRESERVE trial treated 121 patients with organ-confined Grade Group 2-3 intermediate-risk disease. At 12 months, the primary intention-to-treat negative in-field biopsy rate for any Gleason-gradable cancer was 71% (86/121; 95%CI: 62%-79%); using the Delphi criterion for absence of clinically significant cancer, the negative in-field rate was 84% (95%CI: 76%-90%). Urinary scores changed little on average, and 84% of patients with good baseline sexual function maintained erections sufficient for penetration. Fourteen patients (12%) experienced grade ≥ 3 adverse events, including three procedure-related grade 3 events[38]. Its single-arm design and 12-month follow-up limit direct comparison with longer-term cohort estimates of FFS or residual disease.

Therefore, data on continence preservation with IRE are relatively stable, but sexual function is not completely unaffected, and residual local disease still exists. At present, the most appropriate interpretation is that IRE has demonstrated tissue-preserving potential in selected cohorts, but high-quality comparative trials are still lacking to show that it is superior to other focal modalities.

Transurethral ultrasound ablation

Transurethral ultrasound ablation (TULSA) delivers outward circumferential ultrasound from a transurethral applicator and, in combination with real-time MRI thermometry, enables whole-gland or partial-gland ablation. Unlike the transperineal needle-based approach, its technical characteristic is a more controllable treatment path, with dynamic adjustment of energy deposition according to the real-time thermal map; thus, in theory, it may offer both precision and safety.

At present, this advantage is reflected mainly in early functional outcomes. A systematic review including 10 studies and 224 patients showed retreatment rates of 7%-17% after a single TULSA session, continence preservation rates of 92%-100%, erectile function preservation rates of 75%-98%, and a 6% rate of grade III adverse events, with no rectal injury or grade IV complications reported[39]. These findings suggest that TULSA has substantial promise from a functional perspective, although current evidence still comes mainly from early single-arm studies and its long-term oncological role requires cautious interpretation.

Focal laser ablation

Focal laser ablation (FLA) delivers thermal energy precisely to the target lesion through optical fibers and has mainly been evaluated in smaller, well-demarcated lesions visible on MRI. Because the treatment field is limited and the access route is relatively precise, FLA is often regarded as a minimally invasive focal technique. Published FLA cohorts have included heterogeneous populations spanning low- to intermediate-risk disease, precluding definition of a single universal indication.

However, current evidence suggests that the main issue with FLA is not short-term feasibility, but rather fragmented research and nonuniform outcome assessment. A 2026 systematic review and meta-analysis including 12 studies and 421 patients reported a 15% recurrence rate of clinically significant cancer and a mean prostate-specific antigen (PSA) decline of 2.3 ng/mL at 12 months; although sexual function declined statistically, the effect size was small, and urinary function showed no significant change[40]. Another 2024 systematic review and network meta-analysis of MRI-guided FLA included 9 trials and 296 patients, and reported a residual lesion rate of 20.37%, a cancer-free survival rate of 75.62%, and a combined rate of major and minor complications of 14.26%[41]. Thus, based on current data, the advantages of FLA appear to lie in low invasiveness and limited functional impairment, but the absence of a standardized reassessment pathway and of high-quality comparative studies remains a key barrier to its broader adoption.

Vascular-targeted photodynamic therapy

Vascular-targeted photodynamic therapy (VTP) involves intravenous administration of a photosensitizer followed by activation with laser light of a specific wavelength, thereby inducing destruction of the tumor-feeding vasculature. Unlike thermal ablation, its potential advantage lies in the possibility of relatively selective treatment of the targeted region, with comparatively limited direct injury to the urethral sphincter and NVBs; it is therefore particularly relevant when asking whether control and function preservation can be balanced within a narrow set of indications.

The most persuasive data for VTP currently come from a phase III randomized controlled trial. Azzouzi *et al.* randomized 413 men with low-risk localized prostate cancer to VTP or active surveillance. At 24 months, disease progression rates were 28% and 58%, respectively, while negative biopsy rates were 49% and 14%; grade 3-4 adverse events were infrequent, and although urinary retention was relatively common, it usually resolved within 2 months[42]. Thus, randomized evidence for VTP in low-risk localized disease is relatively clear, but its conclusions apply mainly to a narrowly defined indication and cannot be generalized to a broader population with localized prostate cancer. Table 2 provides a descriptive summary of representative studies stratified by ablative modality.

Available cross-study data support descriptive synthesis but not reliable comparative ranking. A 2025 systematic review and meta-analysis of 49 cohorts found no significant between-modality differences in pooled outcomes for focal cryotherapy, HIFU, and IRE; however, these were indirect cross-study comparisons limited by substantial heterogeneity and did not constitute head-to-head evidence[54]. Cryotherapy and HIFU have broader published experience and often report favorable continence outcomes. IRE and TULSA have reported relatively favorable urinary and sexual functional outcomes in selected cohorts, but current evidence does not establish that they provide superior protection of sexual function. FLA studies include heterogeneous risk groups, including low- to intermediate-risk disease, whereas the pivotal randomized VTP evidence was restricted to a low-risk population. FLA and VTP have distinct evidence bases, and a single pooled 5-year residual or recurrence estimate cannot be derived from studies using incompatible endpoints and follow-up durations.

Table 2. Descriptive summary of representative clinical studies of major focal ablation techniques

Modality	Study	Number of patients	Patient risk group	Efficacy outcomes	Complications/Functional outcomes
Cryotherapy	Shah 2019 Prospective multicenter registry[43]	122; median follow-up 27.8 months	Nonmetastatic clinically significant PCa; NCCN intermediate risk 71.3%, high risk 28.7%	3-year FFS 90.5%; 93.3% in intermediate-risk and 84.7% in high-risk disease	0% required pads; ED 16.1% (5/31)
	Shah 2021 Functional recovery analysis[44]	58 (PROM subgroup of the 122-patient cohort)	Predominantly Gleason 3+4/4+3 and cT2 disease	Return to baseline IPSS: 78% at 12 months, 87% at 18-24 months; return to baseline IIEF-EF: 85% at 12 months, 89% at 18-24 months	Urinary and sexual function recovery were the primary endpoints; high-grade complications were not reported separately
	Tay 2016 Systematic review[33]	272 mandatory re-biopsies; functional data from 1,582 patients	Included studies mainly involved localized PCa with heterogeneous risk stratification	Positive biopsy rate on follow-up 21.8%	Continence 96%-100%; ED 0%-42%; urinary retention 0%-15%; rectourethral fistula 0%-0.1%
HIFU	Rischmann 2017 Prospective multicenter hemiablation study[45]	111	Unilateral, localized disease, predominantly favorable-risk	1-year freedom from clinically significant cancer 95%; 2-year freedom from radical treatment 89%	12-month continence 97%; erectile function preservation 78%; grade 3 adverse events 13%
	Guillaumier 2018 Multicenter 5-year cohort[34]	625; median follow-up 56 months	Clinically significant, nonmetastatic PCa; 84% intermediate/high risk	5-year FFS 88%; MFS 98%; CSS 100%; OS 99%	241/247 (98%) completely pad-free; any pad use 2%
	Shoji 2025 Multicenter prospective study[46]	240; median follow-up 48 months	D'Amico low risk 51, intermediate risk 107, high risk 82	Biochemical DFS after single treatment: 93.7%/88.5%/84.8% (low/intermediate/high risk); pathological DFS: 92.2%/91.6%/86.6%	Urinary and sexual function declined transiently at 1 month and returned to baseline by 3-6 months
	Blazevski 2020 Prospective biopsy-monitored cohort[47]	123	Localized clinically significant PCa	No residual lesion on follow-up biopsy in 90.2%-97.3%; 3-year avoidance of whole-gland treatment 96.75%	Minimal overall impact on quality of life
IRE	TARGET study (Fainberg 2024)[36]	20 enrolled, 19 treated	Intermediate-risk PCa	No clinically significant cancer in the whole gland at 12 months in 74%; 2- and 4-year freedom from radical treatment 79% and 73%	No clear decline in urinary or sexual function scores at 6 months
	Scheltema 2023 5-year cohort[37]	229; median follow-up 60 months	86% intermediate risk, 7% high risk	FFS: 91% at 3 years, 84% at 5 years, and 69% at 8 years; MFS 99.6%; CSS/OS 100%	Continence 98% → 99%; erections sufficient for intercourse 71% → 58%; residual csPCa on follow-up biopsy 24%
IRE	George 2026 PRESERVE prospective multicenter single-arm trial[38]	121; 12 months	Organ-confined GG2-3 intermediate-risk disease; cT1-T2c	12-month negative in-field biopsy: any Gleason-gradable cancer 71% (86/121); no csPCa by Delphi criterion 84%	Small mean urinary-score changes; 84% with good baseline sexual functionmaintained penetration-sufficient erections; grade ≥ 3 adverse events 12% (14/121), including 3 procedure-related events

	Dora 2022 Systematic review[39]	10 studies, 224 patients	Localized PCa; heterogeneous inclusion criteria	Retreatment rate 7%-17%	Continence 92%-100%; erectile function preservation 75%-98%; grade III adverse events 6%; no rectal fistula or grade IV complications
TULSA	Nair 2021 Prospective phase I study, 3-year outcomes[48]	30	Localized PCa; predominantly low risk	csPCa in 10/29 (34%) at 3 years; PSA nadir 0.33 ng/mL, approximately 0.8 ng/mL at 3 years	No new severe complications between years 1 and 3; urinary and bowel function stable; erectile function recovered by 1 year and was maintained
	Klotz 2021 Prospective TACT study[49]	115	Low- to intermediate-risk; GG2 63%, NCCN intermediate risk 67%	PSA reduction ≥ 75% in 96% (110/115); no cancer on 12-month biopsy in 65% (72/111)	Grade 3 adverse events 8%; 96% returned to baseline urinary continence; 75% of potent men maintained or regained penetration-sufficient erections
	Bushati 2026 Systematic review/meta-analysis[40]	12 studies, 421 patients	Localized PCa with heterogeneous risk stratification	Clinically significant cancer recurrence 15%; mean PSA decline 2.3 ng/mL at 12 months	Mild decline in sexual function; no significant change in urinary function
	Marcelin 2024 Systematic review/network meta-analysis[41]	9 trials, 296 patients	Mainly MRI-visible lesions	Residual lesion rate 20.37%; cancer-free survival 75.62%	Combined rate of major and minor complications 14.26%
FLA	Eggener 2016 Phase II study[50]	27	Highly selected localized PCa	Negative biopsy in the ablation zone in 26/27 (96%) at 3 months; favorable 1-year oncological outcomes	Acceptable urinary, erectile, and bowel toxicity
	Walser 2019 Cohort of 120 patients[51]	120	Low- to intermediate-risk disease	Freedom from retreatment at 1 year 83%; median PSA reduced to 3.25 ng/mL at 12 months	No significant decline in urinary or sexual function; mild hematuria common; 2 early rectourethral fistulas
	Chao 2021 5-year follow-up[52]	36 enrolled, 30 evaluable; median follow-up 71 months	cT1c-T2a, PSA < 10, GG < 4	5-year FFS 83%; local recurrence 40%; 2 metastases; no PCa deaths	Repeat focal or whole-gland salvage treatment was relatively common
	Taneja 2016 Phase I/II multicenter study[53]	30	Unilateral, low-volume, Gleason 3+3 low-risk disease	When optimized dose plus LDI ≥ 1 was achieved, the negative biopsy rate in the treated lobe was 73.3%	Minimal impact on urinary function, sexual function, and overall quality of life
VTP	Azzouzi 2017 Phase III randomized controlled trial[42]	413; 24-month follow-up	Low-risk localized PCa	Disease progression at 24 months: 28% *vs.* 58%; negative biopsy 49% *vs.* 14% (control: active surveillance)	Few grade 3-4 adverse events; urinary retention was more common but usually resolved within 2 months

Endpoints, patient selection criteria, follow-up schedules, and definitions of functional and oncological outcomes vary substantially across studies; accordingly, this table is intended as a descriptive summary rather than a head-to-head ranking of focal modalities. CSS: Cancer-specific survival; DFS: disease-free survival; ED: erectile dysfunction; FFS: failure-free survival; FLA: focal laser ablation; GG: Grade Group; HIFU: high-intensity focused ultrasound; IIEF-EF: International Index of Erectile Function erectile function domain; IPSS: International Prostate Symptom Score; IRE: irreversible electroporation; LDI: light density index; MFS: metastasis-free survival; MRI: magnetic resonance imaging; NCCN: National Comprehensive Cancer Network; OS: overall survival; PCa: prostate cancer; PROM: patient-reported outcome measure; PSA: prostate-specific antigen; TULSA: transurethral ultrasound ablation; VTP: vascular-targeted photodynamic therapy; csPCa: clinically significant PCa.

Treatment selection should be individualized through multidisciplinary and shared decision-making that considers tumor risk, lesion distribution, life expectancy, baseline function, patient preferences, and willingness to undergo repeat biopsy, retreatment, or salvage therapy. For higher-risk or multifocal localized disease, guideline-concordant management may include RP as part of a multimodal strategy or radiotherapy with systemic therapy when indicated. Within this shared decision-making process, focal therapy may be discussed with carefully selected, fully informed patients, although it is not yet a standard option[32]; some focal modalities are already used in selected clinical settings, including outside formal trials where locally permitted. Counseling should address limitations in comparative and long-term evidence, structured

surveillance, and possible repeat or salvage treatment; availability, regulation, reimbursement, and implementation remain jurisdiction-specific.

AI-ASSISTED SURGERY

With the continued refinement of minimally invasive RP and focal ablative techniques, a central challenge in function-preserving treatment is not simply whether a procedure can be performed, but how accurately surgeons can select candidates, individualize nerve-sparing or ablative strategies, and anticipate both oncological and functional outcomes. AI is increasingly being explored as an adjunct across the surgical workflow, including preoperative risk stratification, MRI-based segmentation and 3D planning, intraoperative navigation, outcome prediction, and workflow optimization. Most evidence remains concentrated in diagnostic imaging, digital pathology, and retrospective prognostic modeling, although the RIDERS trial provides early randomized evidence for 3D-AI-AR guidance during selected nerve-sparing RARP[31,55]. AI should therefore be regarded as an emerging decision-support and guidance technology rather than an established intraoperative standard for function preservation.

Preoperative risk stratification and surgical decision support

In function-preserving surgery, decisions regarding whether and to what extent the NVB should be preserved, which surgical access route should be selected, and whether focal ablation is appropriate depend on accurate assessment of tumor aggressiveness, extracapsular extension, lymph node involvement, and patient-specific competing risks. AI models may contribute by integrating clinical, imaging, biopsy, and pathological variables into individualized risk estimates. A systematic review comparing MRI-based AI methods with conventional clinical assessment showed higher areas under the summary receiver operating characteristic curves (SROC-AUCs) for AI in clinically significant prostate cancer detection (0.87 *vs.* 0.82) and adverse pathology prediction (0.86 *vs.* 0.75), although the authors emphasized the need for prospective validation and open testing datasets[56].

Several clinical decision-support models further illustrate this potential, but their interpretation should remain cautious. A study based on data from 118,236 patients with localized prostate cancer in the Surveillance, Epidemiology, and End Results (SEER) Program developed a final treatment recommendation model to estimate survival probabilities after surgery or radiotherapy; the radiotherapy and surgery models achieved C-index ranges of 0.735-0.787 and 0.769-0.797, respectively, and patients whose actual treatment was consistent with the model recommendation had higher survival rates[57]. Another SEER-based model using the CatBoost gradient-boosting algorithm and SHapley Additive exPlanations (SHAP) for model interpretation identified T stage, disease stage, age, positive core rate, PSA, and Gleason score as key decision variables, with the 10-year survival rate in patients undergoing RP reported as 89.2%[58]. In a more surgery-specific setting, the Dr. Answer AI clinical decision-support system was developed from 7,128 patients treated with RP and predicted tumor-node-metastasis (TNM) stage, extracapsular extension, seminal vesicle invasion, and lymph node metastasis; the random forest model achieved a 76.98% recall for TNM staging, whereas the k-nearest neighbor model achieved recalls of 80.24%, 98.67%, and 95.45% for extracapsular extension, seminal vesicle invasion, and lymph node metastasis, respectively[59]. These models may support shared decision-making, but they should not be interpreted as replacing guideline-based multidisciplinary assessment.

Image segmentation and 3D surgical planning

Accurate preoperative planning is a prerequisite for individualized nerve-sparing and focal therapy. Deep learning-based prostate MRI analysis has been applied to prostate gland segmentation, lesion detection, volume estimation, and characterization of tumor aggressiveness, thereby providing structured inputs for patient-specific 3D models[60]. In principle, these tools can help delineate the prostate, index lesion, capsule,

urethra, and adjacent structures, and can facilitate MRI-ultrasound or MRI-histopathology registration for treatment planning[61]. For function-preserving surgery, the most clinically relevant application is to convert tumor location and side-specific extracapsular extension risk into a clearer surgical map. Nevertheless, automatic identification of fine structures such as the NVB remains technically challenging, and AI-derived 3D planning should be considered complementary to surgeon interpretation, high-quality mpMRI review, and intraoperative judgment.

Intraoperative navigation and real-time assistance

The role of AI in true intraoperative guidance for prostate cancer surgery remains developmental. The RIDERS randomized trial reported lower overall PSMs, less postoperative radiotherapy, and higher 12-month zero-pad continence with 3D-AI-AR guidance than with cognitive MRI guidance, while potency and short-term biochemical recurrence were similar[31]. These findings constitute direct clinical evidence relevant to margin control and continence, but the trial enrolled 133 selected patients with extracapsular extension or bulging on MRI, follow-up was limited to 12 months, and longer-term replication is needed. Beyond this trial, evidence for surgical step recognition, anatomical landmark detection, instrument tracking, bleeding detection, and automated image registration is derived predominantly from retrospective, feasibility, or technical studies and reviews[62]. Evidence that these applications improve nerve preservation or functional outcomes in routine RARP remains insufficient. AI-based prostate-specific membrane antigen positron emission tomography/computed tomography (PSMA PET/CT) segmentation tools may standardize lesion identification and reporting; for example, the aPROMISE platform was evaluated against a standard image viewer and histopathology in patients undergoing PSMA-radioguided surgery[63]. This evidence supports structured preoperative or perioperative imaging interpretation rather than direct robotic-console navigation.

The integration of fluorescence imaging with AI should also be regarded as a future direction rather than an established clinical standard. ICG-NIRF can visualize periprostatic vascular structures and the landmark artery within the NVB, as discussed above, while AI-based image analysis could theoretically enhance vessel recognition and decision support. However, prospective studies are still needed to determine whether AI-enhanced fluorescence guidance improves functional outcomes beyond expert visual interpretation.

Prediction of functional outcomes and prognostic assessment

Direct prediction of postoperative functional recovery has been investigated, but the evidence remains exploratory. In 100 RARP cases, a deep-learning survival model combining automated surgical performance metrics with clinical features predicted continence recovery with a C-index of 0.60[64]. A single-center study of 101 patients combined intraoperative video snapshots with ensemble machine learning and reported an internally validated area under the curve (AUC) of 0.882 for early continence recovery[65]. A larger referral-center cohort of 8,524 patients developed artificial neural-network models with AUCs of 0.68 for 12-month continence and 0.74 for potency[66]. These studies demonstrate feasibility but differ in endpoints and inputs, and prospective multicenter external validation and evidence of clinical benefit are still limited.

AI has shown increasing value in oncological prognostication, particularly when digital pathology is combined with clinical variables. A digital pathology-based multimodal AI model externally validated using four phase III trial datasets from the Systemic Therapy in Advancing or Metastatic Prostate Cancer: Evaluation of Drug Efficacy (STAMPEDE) platform was prognostic for prostate cancer-specific mortality in men with advanced or high-risk nonmetastatic prostate cancer starting long-term androgen-deprivation therapy[67]. In metastatic hormone-sensitive prostate cancer, a related digital pathology-based AI biomarker was associated with OS, clinical progression, and progression to castration-resistant disease[68]. These studies support AI-based prognostication in their source populations, but their relevance to localized nerve-sparing RARP and postoperative functional or margin outcomes remains unvalidated.

For postirradiation recurrence assessment, Marinkovic *et al.* evaluated machine-learning classifiers in 109 patients treated with external-beam radiotherapy, with or without androgen-deprivation therapy, who were assessed after PSA elevation. The Naive Bayes model achieved 100.0% sensitivity, 92.3% specificity, 94.4% positive predictive value, 100% negative predictive value, and 96.7% predictive accuracy for disease progression[69]. These findings concern postirradiation recurrence and do not establish postoperative predictive performance after RP. In pathology, a systematic review of 80 studies found that most AI algorithms addressed biopsy specimens and achieved good to excellent performance for cancer detection and grading; some studies also linked AI-derived histological features with biochemical recurrence, extraprostatic extension, perineural invasion, and disease-free survival[70]. A separate systematic review of AI for early prostate cancer detection reported potential improvements in diagnostic performance and reporting time[71]. Post-RARP functional prediction has instead been investigated in the dedicated studies summarized above[64-66], although prospective multicenter external validation remains insufficient.

Data standardization, validation, regulation, and clinical implementation

Several barriers limit the immediate translation of AI into routine surgical decision-making. First, many studies are retrospective and single-center, with heterogeneous imaging protocols, scanner platforms, histological staining procedures, and annotation standards, all of which can reduce generalizability[72]. Second, robust external validation remains essential. The Prostate Imaging: Cancer AI (PI-CAI) international paired confirmatory study showed that an AI system achieved a higher area under the receiver operating characteristic curve (AUROC) than the pooled performance of 62 radiologists using Prostate Imaging Reporting and Data System version 2.1 (PI-RADS v2.1) for clinically significant cancer detection (0.91 *vs.* 0.86), but non-inferiority to multidisciplinary routine standard-of-care readings was not confirmed because specificity was slightly lower; the authors therefore emphasized prospective validation before clinical implementation[73].

Regulatory and workflow issues also require caution. Although AI-enabled prostate pathology tools have entered clinical use, regulatory authorization generally applies to adjunctive or secondary review rather than autonomous diagnosis[74]. For example, the U.S. Food and Drug Administration (FDA) De Novo summary for Paige Prostate describes an adjunctive software device intended to assist pathologists in detecting areas suspicious for cancer in prostate biopsy whole-slide images after initial review[75]. Broader implementation will require transparent reporting, continuous performance monitoring, interoperability with picture archiving, pathology, and electronic health record systems, and clear allocation of legal responsibility[76,77]. Explainable AI may partly address the black-box problem: in PI-RADS 3 lesions, an explainable deep learning model improved nonexpert reader confidence and reduced reading time by 58 seconds[78]. Overall, the most appropriate current model is clinician-led human-AI collaboration, in which AI assists risk estimation, visualization, and workflow efficiency while the final surgical and diagnostic decisions remain with the treating team.

CONCLUSION

In summary, current evidence supports a consistent direction for function-preserving treatment of localized prostate cancer: reducing urinary and sexual morbidity should be pursued alongside oncological safety rather than as an independent endpoint. Among radical strategies, minimally invasive RP remains an established curative framework, and MP-RARP currently has the most mature evidence base for balancing cancer control and functional preservation. However, the apparent advantages of specific platforms, dissection routes, or adjunctive technologies must be interpreted in light of patient selection, surgeon experience, endpoint definitions, and follow-up duration. Early randomized evidence for 3D-AI-AR guidance is encouraging, but other AI applications remain predominantly exploratory and require prospective external validation.

For carefully selected patients with localized disease, focal ablative modalities provide additional function-preserving options. Reported benefits include lower treatment burden and favorable continence outcomes in selected cohorts, whereas the degree and durability of sexual function preservation and long-term oncological control remain variable. The available heterogeneous evidence neither establishes superiority among focal modalities nor supports routine substitution of focal therapy for guideline-concordant RP, radiotherapy, or active surveillance. Selection should be individualized through multidisciplinary shared decision-making with carefully selected, fully informed patients. Focal therapy is not yet a standard option, but some focal modalities are already used in selected clinical settings, including outside formal trials where locally permitted. Counseling should address limited long-term evidence, structured surveillance, and possible repeat or salvage treatment. EAU guidance continues to emphasize prospective evidence generation through modality-specific registry and trial recommendations, while implementation remains jurisdiction-specific. Future research should refine nerve-sparing, image-guided navigation, AI-assisted decision support, and functional reconstruction while standardizing endpoints and follow-up.

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All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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