International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
editorial_office@rsglobal.pl

ARTICLE TITLE	ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN PREDICTING PROGRESSION AND RECURRENCE OF PROSTATE AND BLADDER CANCER: CURRENT INSIGHTS AND FUTURE DIRECTIONS
DOI	https://doi.org/10.31435/ijitss.4(48).2025.4312
RECEIVED	17 October 2025
ACCEPTED	21 December 2025
PUBLISHED	24 December 2025
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ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN PREDICTING PROGRESSION AND RECURRENCE OF PROSTATE AND BLADDER CANCER: CURRENT INSIGHTS AND FUTURE DIRECTIONS

Krystian Czyżykowski *(Corresponding Author, Email: kianczyzyk@gmail.com)*
Antoni Jurasz University Hospital, Bydgoszcz, Poland
ORCID ID: 0009-0006-8816-1811

Anna Maria Gęsińska
Antoni Jurasz University Hospital, Bydgoszcz, Poland
ORCID ID: 0009-0004-4336-8873

Helena Szelka
University Clinical Hospital No. 2 of the Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0001-7142-341X

Bartosz Golis
Central Clinical Hospital of the Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0007-2968-6797

Paweł Edyko
Central Clinical Hospital of the Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0009-6764-3434

Alicja Babula
T. Marciniak Lower Silesian Specialist Hospital – Centre for Emergency Medicine, Wroclaw, Poland
ORCID ID: 0009-0003-0573-5022

Wiktor Golus
University Clinical Hospital No. 2 of the Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0009-1930-9837

Katarzyna Andrzejewska
Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0001-6994-7505

Zuzanna Przybyła
Medical University of Łódź, Łódź, Poland
ORCID ID: 0009-0009-4778-3106

Hubert Woźniak
Copernicus Memorial Hospital, Łódź, Poland
ORCID ID: 0009-0002-9891-3248

ABSTRACT

Urologic cancers such as prostate and bladder malignancies are characterized by considerable heterogeneity in their biological behavior and clinical outcomes. Accurate prediction of disease progression and recurrence plays a critical role in improving treatment planning, optimizing follow-up strategies, and advancing personalized medicine. Traditional prognostic tools, which rely primarily on clinical and pathological features, often lack the precision required for individualized risk assessment. In recent years, Artificial Intelligence and Machine Learning have emerged as powerful tools in oncological research, offering approaches to prognostic modelling based on large-scale, high-dimensional data.

This review synthesizes findings from thirty-nine recent studies that investigated the use of artificial intelligence in predicting progression, recurrence, survival, and treatment outcomes in prostate and bladder cancers. The included works applied diverse machine learning techniques to data types such as magnetic resonance imaging, whole-slide pathology images, gene expression profiles, and electronic health records. Many models demonstrated improved predictive performance over traditional methods, particularly when integrating multimodal datasets. Furthermore, external validation in multicenter cohorts was increasingly reported, supporting the generalizability of results.

Despite promising advances, the widespread clinical application of artificial intelligence in urologic oncology remains limited. Challenges include variability in data sources, lack of standardization, limited interpretability of models, and ethical concerns related to data privacy and fairness. Nonetheless, the integration of artificial intelligence into clinical decision-making workflows holds substantial promises for enhancing prognostic accuracy and supporting personalized management strategies. Future efforts should focus on harmonized methodologies, prospective validation, and transparent reporting to fully realize the clinical potential of these technologies.

KEYWORDS

Artificial Intelligence, Machine Learning, Prostate Cancer, Bladder Cancer, Prognostic Modelling, Recurrence Prediction

CITATION

Krystian Czyżykowski, Anna Maria Gęsińska, Helena Szelka, Bartosz Golis, Paweł Edyko, Alicja Babula, Wiktor Golus, Katarzyna Andrzejewska, Zuzanna Przybyła, Hubert Woźniak. (2025). Artificial Intelligence and Machine Learning in Predicting Progression and Recurrence of Prostate and Bladder Cancer: Current Insights and Future Directions. *International Journal of Innovative Technologies in Social Science*. 4(48). doi: 10.31435/ijitss.4(48).2025.4312

Introduction

Prostate and bladder cancers represent two of the most prevalent and clinically significant malignancies in urologic oncology. Prostate cancer is the most diagnosed cancer among men in many Western countries and remains a leading cause of cancer-related mortality worldwide (Li et al., 2025). Bladder cancer, on the other hand, is associated with high recurrence rates and long-term morbidity, particularly among patients with non-muscle-invasive disease (Kwong et al., 2024; Abbas et al., 2025). Accurate prediction of tumor progression and recurrence is critical to improving clinical decision-making, optimizing surveillance protocols, and guiding personalized treatment strategies.

Traditional prognostic models, such as the CAPRA score, EORTC risk tables, and CUETO models, rely on limited clinical and pathological parameters and are often constrained by moderate predictive accuracy (Jobczyk et al., 2022; Ferro et al., 2023). In recent years, artificial intelligence and machine learning have emerged as transformative tools capable of handling high-dimensional, heterogeneous data and uncovering complex patterns not readily detectable by conventional methods (Bang et al., 2025; Xu et al., 2022). These technologies have shown promise in enhancing prognostic modelling through integration of clinical, imaging, histopathological, and genomic data (Wang et al., 2025; Zhu et al., 2024b). This trend is further illustrated by Tătaru et al. (2021), who reviewed emerging AI and ML applications across the prostate cancer care continuum — from early diagnosis and biopsy interpretation to risk stratification and treatment selection — emphasizing their transformative potential in personalized management.

Numerous studies have demonstrated that machine learning algorithms can outperform traditional risk models in predicting outcomes such as biochemical recurrence (BCR) in prostate cancer or recurrence and

progression in bladder cancer (Simon et al., 2025; He et al., 2024; Liu et al., 2024). Despite this potential, challenges remain in terms of clinical validation, interpretability, and implementation in routine care. The aim of this review is to provide a comprehensive synthesis of current applications of artificial intelligence in prognostic prediction for prostate and bladder cancer, identify common trends and limitations, and discuss future directions for clinical translation.

Materials and Methods

This narrative review was designed to comprehensively evaluate the current state of research on the use of artificial intelligence and machine learning in predicting disease progression, recurrence, and survival in patients with prostate and bladder cancer. Rather than conducting a systematic search, this study was based on a curated dataset of 39 peer-reviewed articles published between 2021 and 2025. These articles were pre-selected through manual identification and expert screening based on their relevance to the research scope and their scientific rigor.

The inclusion criteria were as follows:

- original research or systematic review.
- focus on either prostate or bladder cancer.
- use of artificial intelligence or machine learning methods applied to prognostic modelling.
- prediction of clinically relevant outcomes, including but not limited to biochemical recurrence, disease progression, cancer-specific survival, or overall survival.
- use of structured input data (e.g., radiologic imaging, histopathology, genomics, clinical records).
- published in a peer-reviewed journal in English.

Articles focused exclusively on renal or testicular cancers, editorials, conference abstracts, or commentaries were excluded. Each included study was analyzed according to predefined categories: cancer type, type and source of input data, machine learning methodology, predicted endpoint, performance metrics (e.g., area under the curve, accuracy, concordance index), validation strategy (internal vs. external), and reported clinical implications.

All information was extracted manually and entered into a structured evidence matrix to facilitate thematic synthesis. This approach enabled the identification of prevailing trends, methodological commonalities, performance benchmarks, and recurring limitations across the included studies. The findings are presented descriptively and summarized in comparative tables to support interpretation and future research planning.

Results

The findings from the reviewed studies on the application of AI and ML in predicting prostate and bladder cancer outcomes are presented below. The results are structured into two main categories: prostate cancer and bladder cancer, with corresponding summary tables.

Prostate Cancer

AI and ML techniques have demonstrated significant prognostic potential in prostate cancer. Various models utilizing clinical, histological, imaging, and molecular data have achieved strong predictive metrics for endpoints such as biochemical recurrence (BCR) and long-term survival. Several studies utilized digital pathology, particularly whole-slide histopathology images (WSI), in combination with clinical or imaging features for recurrence prediction. Many models reported AUCs and C-indices between 0.80 and 0.91, especially when leveraging multimodal data or deep learning (DL) architectures (See Table 1 for a detailed summary of models, inputs, and performance metrics.). Internal and external validations were employed in several studies, supporting the models' generalizability.

Table 1. Summary of AI-Based Prognostic Models in Prostate Cancer

Authors (Year)	Data Type	AI/ML Model	Endpoint	Performance	Validation
Bergero et al. (2025)	Clinicopathological variables	XGBoost classifier	Early BCR	AUC = 0.91	Internal and external
Cao et al. (2025)	Digitized biopsy WSI	Deep learning (MIL framework)	BCR	AUC = 0.91	Internal
Hu et al. (2024)	WSI + biparametric MRI + clinical	Multimodal DL + clinical integration	BCR-free survival	C-index = 0.86	Multicenter
Piran Nanekaran et al. (2024)	MRI + clinical/pathological	Fused radiomics-clinical ML	Post-RT BCR	AUC = 0.84	Internal
Peng et al. (2025)	SEER clinical data	LightGBM	1-, 3-, 5-year survival	AUC = 0.80–0.81	Internal
Wang et al. (2025)	Gene expression + clinical	LASSO + ML	BCR	Reported satisfactory (no value)	Internal

Note: BCR – biochemical recurrence; WSI – whole-slide imaging; DL – deep learning; RT – radiotherapy; MRI – magnetic resonance imaging.

Bladder Cancer

In bladder cancer, AI-driven models have been utilized to predict recurrence, progression, and survival. Digital pathology, radiomics, and SEER-based studies revealed that ML tools outperform traditional risk scores. Models based on histopathology or imaging achieved C-indices ranging from 0.66 to 0.85. Gene expression integration further improved survival prediction, and several models showed consistent accuracy in multicenter validations (Table 2 summarizes the main AI models developed for bladder cancer prognosis).

Table 2. Summary of AI-Based Prognostic Models in Bladder Cancer

Authors (Year)	Data Type	AI/ML Model	Endpoint	Performance	Validation
Jobczyk et al. (2022)	Clinical (EORTC/CUETO variables)	Deep learning recalibration	Recurrence, progression (NMIBC)	C-index improved (value not reported)	External
He et al. (2024)	Histopathology WSI	CNN variants (MacroVisionNet, UniVisionNet)	Overall survival	C-index = 0.66–0.85	Multicenter
Wang et al. (2023)	Multiphase CT	Deep learning signature	Recurrence	High AUC (external validation)	Multicenter
Dai et al. (2025)	SEER data + hospital cohort	LightGBM	5-year cancer-specific mortality	AUC = 0.884, C-index = 0.791	External
Fan et al. (2025)	Post-cystectomy clinical data	Random forest	Urethral recurrence	AUC = 0.778	Multicenter
Tang et al. (2024)	Gene expression + clinical	Random forest + Cox regression	Overall survival	C-index increased (0.68 to 0.75)	Internal

Note: AUC – area under the curve; C-index – concordance index; NMIBC – non-muscle-invasive bladder cancer; WSI – whole-slide imaging; CT – computed tomography.

Discussion

AI in Bladder Cancer: Diagnostic and Prognostic Advances

In bladder cancer, artificial intelligence techniques have been applied across the spectrum from diagnosis to prognosis. Diagnostic applications include image-based tumor detection and pathology analysis. For example, deep learning models have demonstrated remarkable proficiency in analyzing bladder cancer histopathology images, achieving accurate tumor segmentation and grading (Bashkami et al., 2024). This can enhance early detection by reducing subjectivity and interobserver variability in tasks like cystoscopy interpretation or urine cytology analysis (Bashkami et al., 2024). AI-driven image processing (e.g. on cystoscopic or radiologic images) has been shown to improve the identification of subtle tumor features that clinicians might overlook (Bashkami et al., 2024). Digital pathology is another frontier: recent studies show that AI can grade tumors and even predict outcomes from whole-slide images, though most are still at the proof-of-concept stage (Bashkami et al., 2024). Khoraminia et al. (2023) found that computational pathology ("CPATH") methods can stratify bladder cancers into prognostic subgroups based on histological patterns, highlighting the promise of AI in pathological assessment. Overall, these diagnostic innovations could reduce the need for invasive procedures by providing non-invasive or automated alternatives for tumor detection and monitoring (Bashkami et al., 2024).

Prognostic models in bladder cancer have seen a surge of machine learning (ML) and deep learning approaches, particularly for Non-Muscle Invasive Bladder Cancer (NMIBC) which has notoriously high recurrence rates (Abbas et al., 2025). Traditional risk scoring systems (e.g. EORTC tables) often overestimate recurrence risk and have limited accuracy (Abbas et al., 2025). In response, numerous studies have trained ML models on clinical variables, molecular markers, and imaging features to predict outcomes like recurrence, progression, and survival (Abbas et al., 2025; Kwong et al., 2024). These models often outperform the conventional prognostic tools in accuracy and discrimination (Kwong et al., 2024). For instance, Abbas et al. (2025) systematically reviewed 25 ML-based NMIBC studies and reported that advanced algorithms such as neural networks achieved predictive accuracies up to ~97% in recurrence prediction when multi-modal data were used (Abbas et al., 2025). Complementing these findings, Porreca et al. (2024) applied ML to a large multicenter dataset of high-risk NMIBC patients and demonstrated that time to progression was the strongest independent predictor of cancer-specific survival. Their work reinforces the value of AI in identifying nuanced prognostic variables beyond conventional risk scores. Simpler models (e.g. logistic regression) tended to lag behind, especially for complex multi-dimensional data (Abbas et al., 2025). Notably, integrating diverse data types consistently boosted performance: studies combining clinical factors with radiomics (imaging features) or genomics showed higher accuracy than those using single data sources (Abbas et al., 2025). For example, one multimodal model incorporating MRI radiomics, pathology, and genomic markers outperformed models using any single modality alone (Abbas et al., 2025). Likewise, an integrative approach by Tang et al. (2024) added gene expression profiles to clinical features for bladder cancer survival prediction and significantly improved the model's prognostic power (as compared to using clinical data only).

Another study by Zhang and Ma (2024) illustrates how ML can unveil novel prognostic biomarkers: by screening >30 clinical variables, their algorithms identified that a simple combination of serum total bilirubin (TBIL) and tumor marker CA50 was the best predictor of bladder cancer recurrence, outperforming traditional factors (Zhang X. et al., 2024). Such findings suggest AI can discover or validate unexpected risk factors, leading to more personalized risk stratification.

Real-world validation of these bladder cancer AI models is beginning to emerge. He et al. (2024) developed a deep learning prognostic system for bladder cancer across multiple centers, demonstrating that a model trained on multi-institutional data could achieve robust outcome prediction on external cohorts (addressing generalizability). Similarly, Fan et al. (2025) created an ensemble ML model to predict urethral recurrence after radical cystectomy and showed improved predictive performance compared to prior nomograms, as confirmed by an updated meta-analysis. These advances highlight that AI is not limited to common endpoints; it can be tailored even to infrequent but clinically important outcomes (like urethral tumor recurrence). Moreover, population-level data have been leveraged: a SEER-based study by Dai et al. (2025) applied ML to predict cancer-specific mortality after cystectomy, achieving higher accuracy than standard staging models in identifying high-risk patients. In another SEER analysis, Eminaga et al. (2022) built an AI-driven prognostic tool encompassing multiple urologic cancers (including bladder) and attained a concordance index of about 0.80 for survival prediction on an external test set. This underscores that with large datasets, AI can produce well-calibrated models applicable to broader populations.

According to a 2024 systematic review by Kwong et al., the clinical readiness of AI in bladder cancer remains limited despite encouraging performance results. Their evaluation, conducted using the APPRAISE-AI framework, identified several recurring methodological pitfalls among studies focused on NMIBC prognostication. Most included studies were retrospective, single-center analyses with modest sample sizes (median approximately 125 patients). Common issues included heterogeneous outcome definitions (e.g., recurrence versus progression), insufficient external validation, and a high risk of overfitting due to small datasets. Notably, only one out of the fifteen reviewed studies met high-quality standards. Nonetheless, AI models in these studies generally outperformed traditional prediction tools, particularly in accuracy and sensitivity metrics. A complementary narrative review by Laurie et al. (2024) reinforced these concerns, highlighting that despite growing technical advancements, reproducibility and clinical integration remain limited due to methodological heterogeneity and lack of external validation. These findings suggest that while AI-based approaches hold promise for improving risk stratification and reducing overtreatment in bladder cancer, their integration into routine practice requires greater methodological rigor, broader validation, and standardized reporting. Promisingly, ongoing multi-institutional collaborations and the emergence of AI-specific evaluation frameworks in urology may help address these gaps.

AI in Prostate Cancer: Toward Personalized Prediction

Prostate cancer care has been at the forefront of adopting AI, given the disease's heterogeneity and the need for personalized decision-making. **Diagnostic applications** of AI in prostate cancer are well established in imaging and pathology. On the imaging front, convolutional neural networks have been trained on multiparametric MRI to detect and localize prostate tumors. Notably, a recent international study (PI-CAI 2024) demonstrated that an AI system could match experienced radiologists in identifying clinically significant prostate tumors on MRI, even detecting some lesions missed by human readers (Cicchetti et al., 2025). This suggests AI can augment radiologic screening and potentially reduce unnecessary biopsies. Likewise, in pathology, deep learning algorithms (such as those from the PANDA challenge) have achieved pathologist-level performance in Gleason grading of prostate biopsies (Cicchetti et al., 2025). The FDA's approval of an AI tool (Paige Prostate) for assisting in prostate biopsy diagnosis underscores the clinical progress in this area (Cicchetti et al., 2025). These diagnostic AIs offer consistent analysis of slides and scans, which can standardize care by minimizing variability in interpretations. They also have shown the ability to handle large volumes of cases quickly – for example, an AI can process thousands of MRI images to flag suspicious regions in minutes, a task that would be extremely time-consuming manually (Cicchetti et al., 2025). While further validation is ongoing, the trajectory is clear: AI is becoming a valuable co-pilot for clinicians in prostate cancer detection and grading.

Prognostic and predictive modelling in prostate cancer is an area of intense research, particularly for predicting biochemical recurrence (BCR**)** after primary treatment and other long-term outcomes. BCR (rise in PSA after therapy) occurs in roughly 20–40% of men post-prostatectomy (Cao et al., 2025) and is a critical precursor to metastasis. Traditional nomograms (like CAPRA or MSKCC) use linear models on clinical variables but struggle with the nonlinear interactions of factors in prostate cancer progression (Bang et al., 2025). AI and ML methods offer a way to incorporate complex features (like imaging or genomic data) to improve prognostic accuracy (Bang et al., 2025). A wave of recent studies has leveraged these techniques: a 2024 systematic review by Liu et al. compiled 24 studies on AI for post-prostatectomy BCR prediction, involving over 27,000 patients. One striking finding was that models using radiologic data (MRI-based features) achieved a median AUC of 0.90, significantly higher than models using only pathology (median AUC ~0.74) or clinical variables (AUC ~0.81) (Liu et al., 2024). In other words, incorporating imaging greatly enhanced prediction of recurrence, highlighting the value of multi-modal data (Liu et al., 2024). This is consistent with individual studies: Lee et al. (2023) and Simon et al. (2025) both developed deep learning models integrating preoperative MRI with clinical factors to predict BCR-free survival after prostatectomy, reporting improved discrimination over clinical risk scores alone (often achieving AUCs in the 0.80–0.90 range in validation cohorts). Similarly, Hu et al. (2024) created a multimodality model that fused whole-slide histopathology images and MRI data for BCR prediction; by combining tumor morphology with imaging findings, their model outperformed either modality alone in identifying high-risk patients. Supporting these results, Singh et al. (2024) evaluated ML and neural network models for predicting BCR after robot-assisted radical prostatectomy (RARP), demonstrating that AI-based models can achieve superior discrimination compared to traditional nomograms. Their findings further validate the use of post-surgical clinical features and highlight the value of model-driven risk stratification in surgical prostate cancer cohorts. These examples illustrate a broader trend

in prostate cancer AI: combining heterogeneous data (MRI, pathology, genomics, etc.) to capture different facets of tumor biology for better prognostic stratification (Bang et al., 2025).

AI models have also been explored for advanced prostate cancer scenarios. For instance, in metastatic castration-resistant prostate cancer (mCRPC), where treatment resistance is common, AI is being used to analyze genomic and clinical data to predict therapy response. Ejaz et al. (2025) discuss how AI-driven approaches can integrate genomics, proteomics, and prior treatment data to identify biomarkers of resistance and suggest the most effective next-line therapies. Such models might forecast which patients will become resistant to androgen receptor pathway inhibitors versus those who might respond to immunotherapy, for example (Ejaz et al., 2025). Although still largely investigational, these tools could guide personalized treatment sequencing in mCRPC, potentially improving outcomes in this aggressive disease. Early results are encouraging, but the authors note significant challenges like data heterogeneity and the need for better regulatory frameworks before clinical implementation.

Beyond recurrence, ML models have been developed to predict other outcomes: metastasis-free survival, cancer-specific survival, and overall survival. Bang et al. (2025) review an upsurge of studies using ML to forecast such endpoints, often employing complex datasets that include not only clinicopathological features but also radiographic data and even population-scale information. For example, prognostic models have incorporated genomic risk scores along with clinical data to predict progression to metastatic disease. Others have used national registry data to predict long-term survival after different treatment modalities. The goal of these efforts is to improve decision-making - e.g., identifying which patients might benefit from adjuvant post-surgery therapy or which might be suitable for active surveillance. One notable study by Wang et al. (2025) presented an integrative ML model that simultaneously predicts the likelihood of a positive biopsy (diagnosis) and the risk of BCR if the patient has cancer, essentially combining detection and prognostication into one framework. Such integrated models represent a step toward *precision oncology*, wherein a patient's initial workup and future risk profile can be assessed together to optimize treatment choices.

Finally, AI has shown value in novel predictive biomarkers for prostate cancer. Peng et al. (2025) developed an interpretable ML model identifying key features associated with highly aggressive prostate cancer, shedding light on how factors like specific gene expression patterns or immune signatures correlate with poor outcomes. Likewise, radiomic features from advanced imaging are revealing non-invasive markers: Luo et al. (2024) demonstrated that features extracted from PSMA PET scans could predict seminal vesicle invasion preoperatively, which could influence surgical planning. These examples underscore AI's potential not only to predict *whether* an outcome will occur, but also to provide insight into *why* – by pointing to which variables (imaging, biomarkers, etc.) drive the risk. In summary, the landscape of AI in prostate cancer is rapidly evolving from diagnostic assistance (in pathology and imaging) to comprehensive prognostic and predictive modelling aimed at tailoring treatment decisions to individual patient risk profiles.

Potential Benefits of AI Implementation in Urologic Oncology

AI-driven tools in urologic oncology offer several promising advantages that align with the goals of precision medicine:

- **Enhanced predictive accuracy and risk stratification:** ML models can uncover complex, non-linear relationships between clinical, pathological, and molecular data. This often translates into more accurate predictions of recurrence or survival than traditional methods. For instance, integrating multi-modal data - including imaging, histopathology, and clinical variables - has allowed AI models to identify high-risk patients with prostate or bladder cancer more precisely, supporting earlier and more targeted interventions such as adjuvant chemotherapy or intensified surveillance (He et al., 2024; Hu et al., 2024; Simon et al., 2025; Wang et al., 2025; Wu et al., 2025). Improved stratification directly enables personalized treatment planning and may help reduce both under- and overtreatment.
- **Early detection and diagnostic consistency:** Beyond prognostic modelling, AI has also improved diagnostic consistency across urologic malignancies. Deep learning algorithms applied to radiological and pathological data have demonstrated high accuracy in detecting and grading urinary tract tumors, reducing interobserver variability and accelerating diagnostic workflows (Ferro et al., 2023; Khoraminia et al., 2023; Li et al., 2025; Vidiyala et al., 2025; Zhu et al., 2024a). These advances directly support personalized treatment planning by providing clinicians with reproducible, data-driven assessments that enhance precision and efficiency in decision-making.

- **Personalized and targeted therapy:** By predicting outcomes such as biochemical recurrence (BCR), progression to metastatic disease, or treatment resistance, AI-based models can help clinicians tailor therapeutic strategies to individual patients. For example, when an ML model identifies a high likelihood of BCR following prostatectomy, clinicians may consider intensified PSA monitoring or adjuvant therapy, whereas patients with a predicted low recurrence risk might safely avoid unnecessary additional treatment (Bergero et al., 2025; Cao et al., 2025; Hu et al., 2024; Simon et al., 2025). In metastatic castration-resistant prostate cancer, AI frameworks can also forecast therapeutic resistance and guide the selection of effective next-line treatments (Ejaz et al., 2025). In bladder cancer, accurate recurrence and progression predictions inform decisions about surveillance intensity and timing of radical interventions, optimizing patient outcomes while minimizing overtreatment (Dai et al., 2025; He et al., 2024; Jobczyk et al., 2022).
- **Automation and efficiency:** Artificial intelligence (AI) systems have shown potential to assist clinicians by automating certain steps of diagnostic evaluation in urologic oncology. Studies have described AI applications in radiology, pathology, and multimodal data integration that may reduce diagnostic subjectivity and improve consistency across readers, indirectly supporting workflow efficiency and timely decision-making (Ferro et al., 2023; Khoraminia et al., 2023; Li et al., 2025; Vidiyala et al., 2025; Zhu et al., 2024a). Although these studies do not provide direct evidence of time reduction or cost savings, they highlight AI's capacity to standardize diagnostic interpretation and streamline processes by supporting clinicians in data-heavy tasks.
- **Educational and transferable insights:** The development of artificial intelligence (AI) in urologic oncology extends beyond direct clinical applications, offering methodological and educational benefits. As noted by Abbas et al. (2025), the analytic principles and architectures applied to predict recurrence in non-muscle-invasive bladder cancer can often be adapted to other oncologic contexts, such as muscle-invasive disease or prostate cancer, emphasizing the transferability of AI-driven methodologies across related domains. Similarly, interpretability in AI models provides an additional layer of educational value. Models capable of visualizing or quantifying which histologic or radiologic features drive a given prediction may assist trainees in understanding which parameters carry prognostic weight in clinical practice (Cao et al., 2025). Furthermore, the integration of AI into oncologic research fosters stronger collaboration between clinicians, pathologists, and data scientists, helping bridge the gap between computational innovation and clinical utility. Such interdisciplinary work not only improves model design and validation but also accelerates the translation of AI tools into routine practice (Cicchetti et al., 2025; Li et al., 2025).

In essence, the promise of artificial intelligence (AI) in urologic oncology lies in achieving greater precision and consistency in patient care. Across studies of both bladder and prostate cancer, AI-based systems have demonstrated superior predictive accuracy compared with conventional models, as well as improved reproducibility in diagnostic and prognostic assessments (Abbas et al., 2025; Ferro et al., 2023; Khoraminia et al., 2023; Li et al., 2025). By enhancing prediction accuracy and minimizing interobserver variability, these technologies can support earlier, more individualized interventions while reducing unnecessary procedures and associated morbidity. When thoughtfully implemented, AI serves not as a replacement for clinical expertise but as a powerful adjunct in decision-making, reinforcing the shift toward data-driven precision oncology.

Challenges and Future Directions

While the potential benefits are substantial, there remain significant challenges and pitfalls that must be addressed before AI achieves widespread clinical adoption in urologic oncology:

- **Data quality, bias, and generalizability:** The reliability of artificial intelligence (AI) models in urologic oncology depends largely on data quality and diversity. Many studies are based on retrospective, single-center datasets, which heightens the risk of overfitting and limits generalizability (Abbas et al., 2025; Kwong et al., 2024). Variations in demographics, imaging methods, and histopathological preparation across institutions can introduce systematic bias and reduce model consistency (Cicchetti et al., 2025; Khoraminia et al., 2023). As a result, algorithms trained in one setting often underperform when applied elsewhere. Multicenter collaborations have begun to mitigate these issues. He et al. (2024) showed that integrating data from multiple institutions enhances predictive robustness and reduces bias. Future studies should prioritize diverse, externally validated datasets and incorporate bias detection strategies to ensure equitable and reproducible AI performance across clinical environments.

- **Lack of external validation and prospective trials:** A major limitation of current AI research in urologic oncology is the scarcity of external validation and prospective evaluation. Most studies rely solely on internal testing, which fails to confirm reproducibility across institutions and patient populations (Abbas et al., 2025; Cicchetti et al., 2025; Liu et al., 2024). Systematic reviews consistently show that only a minority of models undergo external validation, and virtually none have been tested in real-world clinical settings (Kwong et al., 2024). Some progress has been made through multicenter studies - He et al. (2024) demonstrated that integrating heterogeneous datasets improves robustness and reduces overfitting - but large-scale prospective trials remain lacking. Until such evidence emerges, AI tools in urologic oncology should be considered promising yet investigational technologies requiring further clinical validation (Cicchetti et al., 2025; Liu et al., 2024)
- **Interpretability and the "black-box" problem:** One of the main barriers to clinical implementation of artificial intelligence (AI) in urologic oncology is the limited interpretability of complex deep learning models. Many high-performing algorithms function as "black boxes," producing accurate predictions without transparent reasoning, which undermines clinician trust and hinders adoption (Abbas et al., 2025; Cicchetti et al., 2025). To address this, recent studies have begun integrating explainable AI (XAI) techniques - such as attention maps, heatmaps, and SHapley Additive exPlanations (SHAP) - to visualize which imaging or histopathologic features drive model predictions (Cao et al., 2025; Li et al., 2025). Such transparency can validate whether the algorithm's focus aligns with established prognostic factors, for example, highlighting perineural invasion in prostate biopsy slides or high-grade histologic patterns in bladder cancer. Hybrid approaches offer another promising solution. Jobczyk et al. (2022) combined a deep neural network with a Cox regression model for bladder cancer, maintaining the interpretability of regression coefficients while leveraging the predictive power of deep learning. Designing models that balance accuracy with interpretability will be essential for gaining clinical acceptance and ensuring safe, explainable AI integration into oncologic decision-making.
- **Integration into clinical workflow:** Integrating artificial intelligence (AI) into real-world urological oncology practice presents both technical and practical challenges. Effective adoption requires that AI tools be seamlessly embedded into existing clinical systems - such as radiology Picture Archiving and Communication System (PACS) or digital pathology platforms - while delivering timely, interpretable results that align with clinical decision-making workflows. If model use is overly complex, time-consuming, or poorly interoperable with hospital IT infrastructure, clinicians are unlikely to adopt it (Cicchetti et al., 2025; Li et al., 2025). Clear guidance on how AI-derived predictions should influence management decisions is also essential; for example, an elevated recurrence risk predicted for a patient categorized as low risk could alter surveillance or adjuvant treatment planning (Riaz et al., 2024). Furthermore, engaging end-users - including urologists, oncologists, radiologists, and pathologists - in tool design and validation can improve usability and ensure that clinical decision support systems generate actionable, rather than ambiguous, recommendations (Ferro et al., 2023; Khoraminia et al., 2023).
- **Regulatory and ethical considerations:** The integration of artificial intelligence (AI) into clinical oncology raises complex regulatory, ethical, and legal questions. Since AI models increasingly influence diagnostic and therapeutic decisions, they may require approval as medical devices, with evidence demonstrating safety, reproducibility, and equitable performance across populations (Cicchetti et al., 2025; Ferro et al., 2023). Regulatory agencies such as the FDA and EMA are still refining frameworks for adaptive algorithms that continue to learn after deployment, posing unique oversight challenges. Ethical considerations are equally important. Ensuring patient privacy and secure data comprehension remains a top priority, especially in digital pathology and large-scale imaging datasets (Khoraminia et al., 2023). Moreover, unrecognized bias in training data can reduce model accuracy in underrepresented groups, potentially worsening existing health disparities (Li et al., 2025). Continuous post-implementation monitoring is therefore recommended to detect performance drift and maintain patient safety (Abbas et al., 2025). Finally, medicolegal accountability must be clarified - if an AI system mispredicts and contributes to harm, it remains unclear whether responsibility lies with the developer, clinician, or healthcare institution (Cicchetti et al., 2025). Establishing clear ethical and legal frameworks will be crucial as AI becomes more deeply embedded in oncologic decision-making.

- **Scientific and clinical culture:** A lasting challenge in integrating artificial intelligence (AI) into urologic oncology is the cultural shift required within medicine itself. Clinical practice has traditionally relied on human expertise, intuition, and established guidelines, whereas AI introduces a paradigm of data-driven decision support. As Cicchetti et al. (2025) emphasize, AI should be viewed as an assistive tool that complements rather than replaces clinical judgment. Building clinician confidence requires clear understanding of both the capabilities and limitations of these systems. Li et al. (2025) highlight that structured education and ongoing training are essential to ensure responsible and informed use of AI in practice. Moreover, fostering collaboration between clinicians and data scientists can bridge knowledge gaps - clinicians gain insight into model mechanisms, while developers learn the nuances of clinical context and outcome relevance (Riaz et al., 2024). Over time, successful clinical implementations, such as AI tools that reliably identify high-grade tumors or reduce unnecessary interventions, will help establish trust and normalize AI-assisted decision-making across oncology disciplines.

Future directions

Future work should prioritize rigorous external validation and prospective evaluation to establish clinical utility beyond single-center, retrospective designs. Systematic reviews consistently highlight the scarcity of high-quality, externally validated studies in bladder cancer and post-prostatectomy recurrence prediction, underscoring the need for multicenter cohorts, harmonized endpoints, and transparent reporting (Abbas et al., 2025; Kwong et al., 2024; Liu et al., 2024). Multimodal integration - combining histopathology, MRI, clinical variables, and, where available, transcriptomics - has repeatedly improved discrimination and risk stratification and should be advanced with standardized pipelines and shared benchmarks (Hu et al., 2024; Simon et al., 2025; Wang et al., 2025). Evidence from multicenter development and validation suggests that heterogeneous datasets mitigate overfitting and enhance generalizability, a direction that warrants expansion through broader collaborations (He et al., 2024; Jobczyk et al., 2022). Parallel efforts should focus on interpretability and clinician-facing explanations to support adoption, building on work with interpretable or explanation-augmented models (Cao et al., 2025; Peng et al., 2025). Finally, implementation research is needed to define workflow integration, decision thresholds, and impact on treatment selection and surveillance intensity, with attention to equity and bias monitoring (Cicchetti et al., 2025; Li et al., 2025; Riaz et al., 2024).

It is important to acknowledge the limitations of this review. As stated in the methodology, this is a narrative review based on expert selection rather than a systematic review. While efforts were made to comprehensively synthesize recent, high-impact studies, the review may not be exhaustive and is potentially subject to unintentional selection bias in the curation of included literature.

Conclusions

In conclusion, across the 39 studies reviewed, AI systems consistently demonstrate superior or at least competitive predictive performance versus conventional tools in prostate and bladder cancer while revealing the importance of multimodal data and robust validation strategies (Dai et al., 2025; Ferro et al., 2023; Khoraminia et al., 2023; Tang et al., 2024; Wu et al., 2025). Real-world impact will depend on moving from promising accuracy to prospectively proven clinical benefit, supported by interpretable models, standardized evaluation, and seamless workflow integration. With these advances, AI can evolve from investigational support to a reliable component of precision urologic oncology (Bergero et al., 2025; Lee et al., 2023; Ma et al., 2024).

Author's Contributions:
Conceptualization: Krystian Czyżykowski
Methodology: Bartosz Golis, Krystian Czyżykowski
Software: Paweł Edyko, Krystian Czyżykowski
Check: Anna Maria Gęsińska. Krystian Czyżykowski
Validation / Check: Wiktor Golus, Krystian Czyżykowski
Formal Analysis: Katarzyna Andrzejewska, Krystian Czyżykowski
Investigation: Bartosz Golis, Krystian Czyżykowski
Resources: Helena Szelka, Krystian Czyżykowski
Data curation: Zuzanna Przybyła, Krystian Czyżykowski
Writing – rough preparation: Hubert Woźniak, Krystian Czyżykowski
Writing – Review and Editing: Alicja Babula, Krystian Czyżykowski
Supervision / Project Administration: Anna Maria Gęsińska, Krystian Czyżykowski

All authors have read and agreed to the published version of the manuscript.

Funding Statement: The author received no external funding for this work.

Institutional Review Board Statement: Not applicable; this review included only published data.

Data Availability Statement: All supporting data are available within the cited peer-reviewed literature.

Acknowledgments: The author acknowledges the contribution of investigators and data curators whose high-quality research underpins the advances reviewed herein.

Conflict of Interest Statement: The author declares no conflict of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process: In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool, the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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