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Review Article

Digital twins in urological oncology and surgery: A review of emerging applications

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ABSTRACT

Background: Digital twin technology represents a transformative approach in healthcare, creating virtual replicas of physical entities that enable real-time data integration, predictive modelling, and personalised treatment strategies. In urology, this emerging technology offers unprecedented opportunities to optimise patient care through simulation-based decision-making.

Aim: This narrative review comprehensively examines current applications of digital twin technology in urology, evaluates its clinical utility across various urological conditions, and identifies key challenges limiting its widespread implementation.

Method: A comprehensive search was conducted across PubMed, Web of Science, and Scopus databases for literature published between January 2020 and January 2026. Search terms included digital twin, virtual twin, urology, uro-oncology, prostate cancer, renal surgery, and bladder dysfunction. Studies focusing on the development, validation, and clinical implementation of digital twins in urological practice were included.

Results: Digital twin technology demonstrates significant potential in uro-oncology for treatment planning, surgical navigation, and disease progression monitoring. Key applications include patient-specific tumour growth simulation in prostate cancer, three-dimensional anatomical modelling for partial nephrectomy, and bladder function prediction in outlet obstruction. Integration with artificial intelligence enhances predictive accuracy and enables real-time surgical guidance.

Conclusion: Digital twin technology represents a paradigm shift towards precision urology, though challenges in data integration, computational requirements, validation, and ethical considerations must be addressed before routine clinical implementation. Future developments should focus on standardisation, regulatory frameworks, and prospective clinical validation studies.

1. Introduction

The concept of digital twin technology, initially developed by NASA for aerospace applications in the early 2000s, has evolved into a transformative paradigm across diverse industries [1,2]. In healthcare, digital twins represent sophisticated virtual replicas of physical entities that continuously update through real-time data exchange, enabling predictive analytics, treatment optimisation, and personalised care delivery [3,4]. This technology integrates multimodal data sources, including electronic health records, medical imaging, genomic information, and

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physiological parameters, to create comprehensive patient-specific models [3,5]. The healthcare digital twin market is expanding rapidly, driven by increasing interest in predictive and personalised healthcare models, although estimates of market size and growth vary considerably [4].

Urology, a specialty characterised by diverse pathological conditions that require precise diagnostic and therapeutic interventions, stands to benefit significantly from the implementation of digital twins. The field encompasses complex disorders ranging from malignancies such as prostate, kidney, and bladder cancer to benign conditions, including lower urinary tract symptoms, urolithiasis, and male infertility [6,7]. Traditional approaches to urological care, while effective, often lack the predictive capacity and personalisation that contemporary precision medicine demands. Digital twins address this limitation by creating patient-specific virtual models that simulate disease progression, predict treatment responses, and guide surgical planning with unprecedented accuracy [8,9].

Recent technological advancements, particularly in artificial intelligence and machine learning, have substantially accelerated the development of digital twins in urology, with a strong focus in uro-oncology and surgical applications. These AI-enabled systems can integrate and process large, multimodal datasets (including imaging, pathology, clinical, and genomic data) to improve predictive accuracy and provide decision support for diagnosis, treatment planning, and intraoperative guidance [9–11]. In uro-oncology, digital twins facilitate tumour growth simulation, prediction of treatment response, and personalised therapy selection. For surgical applications, three-dimensional anatomical digital twins enhance pre-operative planning and provide real-time intraoperative guidance, potentially improving surgical precision and patient outcomes [6,12]. The convergence of imaging modalities, computational power, and algorithmic sophistication has created an environment conducive to the adoption of digital twins in urological practice.

Despite its promising potential, several challenges impede the widespread implementation of digital twins in urology. Technical barriers include computational complexity, difficulties with data integration, and the need for robust validation frameworks [3,13]. Ethical considerations encompass patient data privacy, informed consent for virtual representation, and questions regarding digital twin ownership [2]. Regulatory uncertainties and the absence of standardised guidelines further complicate clinical translation. Additionally, the resource-intensive nature of digital twin development, requiring multidisciplinary expertise and substantial infrastructure investment, presents practical obstacles for many healthcare institutions [8].

The current landscape of digital twin applications in urology remains fragmented, with most implementations confined to research settings and pilot studies [14]. While preliminary evidence suggests clinical utility, comprehensive reviews that synthesise existing knowledge and identify research gaps are scarce. This narrative discusses this gap by systematically examining digital twin applications across urological subspecialties, evaluating their clinical impact, and discussing implementation challenges. The primary aim is to provide a comprehensive overview of current digital twin technology in urology, including applications in uro-oncology, surgical planning, functional urology, and diagnostic enhancement. Secondary objectives include identifying barriers to clinical translation, proposing solutions to overcome implementation challenges, and outlining future research directions. This review offers novel insights by integrating recent developments in artificial intelligence with digital twin technology, provides a contemporary perspective on precision urology, and offers practical recommendations for clinicians and researchers interested in implementing digital twins. As summarised in Fig. 1, contemporary urological digital twins integrate heterogeneous data streams into dynamic, patient-specific models that support predictive analytics and precision intervention across uro-oncology, surgery, and functional urology.

2. Methods

2.1. Search strategy

A comprehensive literature search was conducted to identify relevant studies on digital twin applications in urology. The search encompassed three major bibliographic databases: PubMed, Web of Science, and Scopus. The search strategy employed a combination of medical subject headings and free text terms to maximise the retrieval of pertinent literature. Primary search terms included digital twin, digital patient twin, virtual twin, virtual model, computational model, and in

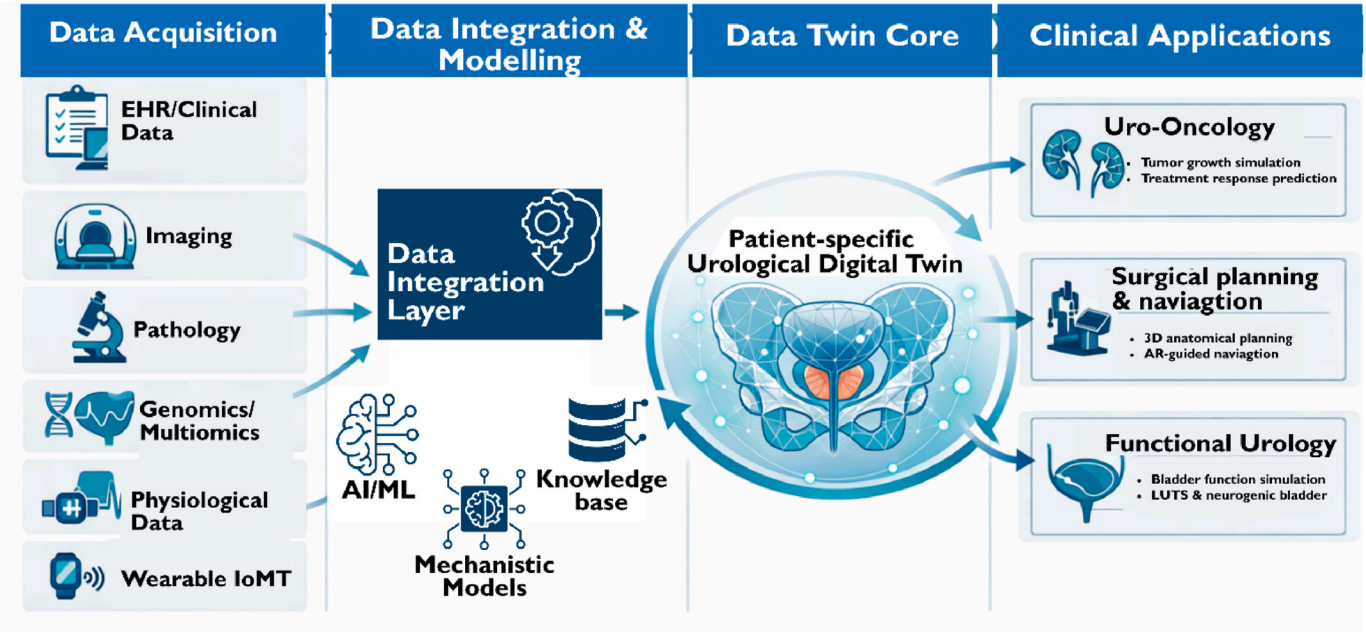

Fig. 1. Conceptual architecture of urological digital twins, illustrating the integration of multimodal data sources, hybrid AI–mechanistic modelling, and a patient-specific virtual replica that continuously updates over time. This framework underpins applications in uro-oncology, surgical planning and navigation, and functional urology, ultimately enabling personalised, predictive, and efficient urological care.

silico model. These were combined with urology-specific terms, including urology, uro-oncology, urological surgery, prostate cancer, renal cancer, bladder cancer, nephrectomy, and urological disease. Boolean operators were utilised to refine the search strategy and capture the breadth of relevant literature.

2.2. Inclusion and exclusion criteria

Studies were included if they described the development, validation, or clinical application of digital twin technology in urological contexts. The review encompassed original research articles, clinical studies, technical reports, and reviews published between January 2020 and March 2026. However, some relevant historic studies were added. This timeframe was selected to capture contemporary developments in the rapidly evolving field while ensuring relevance to current practice. Publications had to be in English and available in full text. Studies were excluded if they focused solely on general healthcare applications without specific urological relevance, described purely theoretical frameworks without practical implementation, or lacked sufficient methodological detail for critical appraisal.

2.3. Data extraction and synthesis

Data extraction followed a narrative synthesis approach, appropriate given the heterogeneity of the included studies. The information extracted included the study design, urological application area, digital twin development methodology, data sources utilised, validation approaches, clinical outcomes reported and identified limitations. The synthesis focused on identifying common themes, technological approaches, clinical applications, and implementation challenges across studies. As a narrative review, no formal quality assessment or meta-analysis was conducted. Instead, the review emphasises comprehensive coverage of the field, critical appraisal of methodological approaches, and integration of findings to provide actionable insights for clinicians and researchers.

2.4. Level of evidence and bias assessment

To contextualise the quality of available evidence, included studies were classified according to the Oxford Centre for Evidence-Based Medicine (OCEBM) 2011 Levels of Evidence framework. This classification assigns studies to levels ranging from 1 (systematic reviews of randomised controlled trials) to 5 (expert opinion and mechanistic reasoning). Given the nascent state of digital twin technology in urology, the majority of included studies represent Level 4 (case series, pilot studies, and technical feasibility reports) or Level 5 (expert opinion, narrative reviews, and proof-of-concept computational models), with a smaller proportion constituting Level 3 evidence (retrospective cohort studies and non-randomised comparative studies). No Level 1 or Level 2 evidence in the form of randomised controlled trials or systematic reviews with pooled quantitative outcomes was identified for digital twin interventions in urology specifically. This distribution reflects the early-phase developmental nature of the field and should be interpreted accordingly when evaluating the strength of reported findings.

A structured assessment of potential bias was conducted for individual primary studies. Computational and predictive modelling studies were evaluated using adapted criteria based on the TRIPOD (Transparent Reporting of a Multivariable Prediction Model for Individual Prognosis or Diagnosis) guidelines and the PROBAST (Prediction Model Risk Of Bias Assessment Tool) framework, which assess participant selection, predictor assessment, outcome measurement, and analytical methods. Observational clinical studies were appraised using the Newcastle–Ottawa Scale (NOS), which evaluates the domains of selection, comparability, and outcome. The review identified several prevalent sources of bias across the included literature, including single-centre designs, small sample sizes, lack of external validation cohorts, and retrospective data collection. Furthermore, the majority of computational models were validated using the same datasets employed for their development, raising concerns about overfitting and limited generalisability to independent patient populations. These limitations are consistent with the early developmental stage of the field and should be carefully considered when interpreting the reported performance metrics and clinical conclusions.

3. Applications in uro oncology

3.1. Prostate cancer management

Prostate cancer represents the most extensively studied application of digital twin technology within urology, particularly compared with bladder and kidney applications [15]. Digital twin–oriented prostate cancer models increasingly integrate multiparametric MRI-derived anatomy and tumour characteristics with longitudinal PSA measurements and Gleason grading, creating patient-specific representations that can simulate tumour burden and PSA kinetics under active surveillance. While fully routine integration of genomic profiling into these imaging–PSA–Gleason frameworks remains emergent, several AI- and digital-twin–focused studies highlight multi-modal pipelines that incorporate molecular features to refine risk stratification and individualised treatment planning in prostate cancer [15–17].

Patient-specific biomechanistic and imaging-informed prostate models have been used to simulate tumour growth dynamics within the gland, forecast changes in tumour volume and PSA levels over time, and explore disease trajectories under active surveillance scenarios. Such models support prediction of progression versus stability with plausible timelines, thereby informing decisions about when to transition from surveillance to definitive treatment in individual patients [16,18]. Recent work has demonstrated physics-informed machine learning frameworks in which a digital twin of the prostate couples a mechanistic model of tumour growth and PSA secretion with deep neural networks that are updated using serial PSA blood tests. In these approaches, the physics-based partial differential equation model encodes tumour biology and PSA transport, while the learned components modulate local proliferation dynamics, enabling reconstruction of patient-specific growth patterns from routine PSA monitoring and an initial MRI. By forecasting future PSA and tumour-volume trajectories with relatively low reconstruction error over multi-year follow-up, these physics-informed digital twins offer a basis for optimising surveillance intervals and timing of intervention [16,18,19]. These approaches suggest the potential to reduce unnecessary biopsies and delayed treatment escalation, although prospective clinical validation is still required.

Patient-specific digital twins for prostate cancer treatment enable simulation of various therapeutic approaches before clinical implementation. Studies have validated digital twin frameworks for predicting pathological staging and biochemical recurrence following radical prostatectomy, achieving prediction accuracies exceeding ninety percent in some cohorts [15]. For radiation therapy, digital twins predict treatment response, facilitate dose optimisation by simulating tumour control probability and normal tissue complication probability across different treatment plans [20]. A recent prostate adaptation describes a mechanistic multiscale model of clinical prostate-cancer response to external radiation therapy as the core of a digital or virtual twin. In that framework, the core tumour model is based on a discrete-entity/discrete-event simulation approach and has been extended through linked submodels for processes such as vasculature, metabolism, signalling, biomechanics, and cell-kill dynamics [21]. Although these multiscale radiotherapy models have clear translational potential for personalised planning and in silico experimentation, it is still emerging and under clinical validation rather than as routinely validated clinical digital twins.

3.2. Renal cell carcinoma

Digital twin applications in renal cell carcinoma focus primarily on surgical planning for partial nephrectomy. Three-dimensional anatomical digital twins reproduce kidney parenchyma, vascular structures, tumour characteristics, and the collecting system with tissue texture derived from intraoperative imaging [8]. These models demonstrate high anatomical fidelity and improved intraoperative interpretability compared with conventional imaging-based reconstructions, which could facilitate identification of tumour margins, vascular pedicle dissection, and preserve renal function. Recent implementations demonstrate enhanced intraoperative guidance via the augmented-reality overlay of digital twin models onto the surgical field, enabling real-time navigation during robotic-assisted partial nephrectomy [8,22].

Machine-learning methods are increasingly integrated with renal 3D virtual models and anatomical digital twins, improving tumour characterisation and intraoperative guidance beyond conventional imaging alone. Computational models incorporating perfusion parameters from dynamic contrast-enhanced imaging predict aggressive tumour behaviour and potential metastatic risk. For complex renal masses with intermediate to high nephrometry scores, digital twins assist surgical decision-making by simulating different resection strategies and predicting functional outcomes. Some studies suggest potential reductions in operative time and improved nephron-sparing, particularly in experienced hands, though results remain heterogeneous [6,23,24].

Table 1 summarises key digital twin applications in uro-oncology, highlighting the specific urological conditions addressed, the primary application domains, and the data sources used for model development.

3.3. Preclinical digital twin models and organoid integration

Digital twins are not confined to clinical settings; their application in the preclinical research phase represents an equally promising frontier, particularly through integration with organoid technology. Organoids are self-organising, three-dimensional cell cultures derived from patient-specific stem cells or tumour-derived tissue that recapitulate the structural, cellular, and functional characteristics of their organ of origin [29]. In urological oncology, patient-derived organoids (PDOs) from prostate, renal, and bladder tumours are established preclinical models for studying tumour biology and inter-patient therapeutic heterogeneity. In prostate cancer, long-term organoid cultures were generated from metastatic biopsies and circulating tumour cells, and later prostate organoid/xenograft platforms were shown to model therapy response [30]. In renal cell carcinoma, patient-derived organoid systems have been reported as personalised platforms for drug testing and individualised therapy. In bladder cancer, PDOs generated from non-muscle-invasive and muscle-invasive tumours preserve histological and molecular heterogeneity and have been used for drug screening, biomarker discovery, and tailored therapy testing [31].

When coupled with computational digital-twin frameworks, however, organoids are best described at present as promising biological counterparts for model calibration and validation rather than components of a mature clinical workflow. Within that emerging paradigm, organoids can contribute the kinds of multimodal and longitudinal measurements that digital-twin systems need, including growth dynamics, genomic or transcriptomic profiles, and drug-response phenotypes. Recent virtual-cell and virtual-organoid reviews explicitly describe a closed-loop workflow in which computational predictions are iteratively checked against organoid or other experimental platforms and then refined; conversely, the in silico model can be used to prioritize candidate perturbations, such as dosing schedules, gene perturbations, and microenvironmental changes, before they are tested experimentally [32,33].

For prostate cancer specifically, it is more accurate at present to say that organoid-informed digital twins are a plausible next step for personalizing androgen-deprivation therapy, rather than an established clinical tool. Patient-specific mathematical models of androgen-ablation therapy already exist, but they have generally been parameterized from clinical observables rather than organoid-derived measurements [34]. Nonetheless, prostate PDOs could, in future, provide experimentally grounded estimates of sensitivity and resistance to strengthen such models. A similarly careful formulation is appropriate for renal and bladder cancers. For example, bladder PDO studies have examined platinum- and olaparib-sensitivity and have also been used to evaluate CAR-T cytotoxicity in vitro, showing how functional ex vivo data could be fed into future digital-twin architectures for simulating therapy response [35,36]. At present, the convergence of PDOs and digital twins in uro-oncology is best framed as an emerging hybrid preclinical strategy that could narrow the gap between functional tumour biology and computational simulation, but that still requires standardized data generation, prospective validation, and demonstration of clinical utility before routine implementation.

4. Surgical planning and navigation

Digital twin-assisted surgery represents a paradigm shift in urological operative planning and execution. Technology enables comprehensive pre-operative simulation, allowing surgeons to rehearse procedures, anticipate complications, and optimise surgical approaches before patient intervention [8,37]. Three-dimensional anatomical digital twins created from pre-operative imaging provide detailed visualisation of organ anatomy, vascular structures, and pathological lesions. During robotic-assisted procedures, real-time digital twin overlay facilitates navigation by displaying virtual anatomy superimposed on the operative field, enhancing spatial orientation and precision [6,37].

For complex urological surgeries such as partial nephrectomy, radical prostatectomy, and cystectomy, digital twins offer substantial advantages. Pre-operative simulation enables the identification of anatomical variations, the assessment of technical feasibility, and the selection of optimal surgical approaches [6]. Intra-operative augmented reality (AR) overlays are increasingly used in urology to project 3D reconstructions of patient anatomy onto the operative field, providing real-time visualisation of tissue boundaries, vascular structures, and tumour margins. These AR-enhanced guidance systems are often coupled with 3D anatomical models or digital-twin-like reconstructions, helping surgeons navigate critical structures more safely during procedures such as robotic partial nephrectomy or prostatectomy [8,37].

Table 1
Digital twin applications in uro-oncology.

Condition	Primary Application	Data Sources	Key Outcomes
Prostate Cancer [15,16,19]	Tumour growth simulation, treatment response prediction, active surveillance optimisation	Multiparametric MRI, PSA values, Gleason score, genomic data	Prediction accuracy exceeding 90% for PSA trajectories and growth in validation cohorts; supports personalised surveillance intervals and treatment guidance
Renal Cell Carcinoma [8,25,26]	Surgical planning for partial nephrectomy, intraoperative navigation, functional-outcome prediction	CT imaging, contrast-enhanced MRI, and intraoperative robotic camera data	Enhanced anatomical concordance, improved tumour/vascular/ureter identification; potential for nephron-sparing
Bladder Cancer [10,27,28]	Treatment response monitoring, recurrence prediction, cystectomy planning	Cystoscopy imaging, urinary biomarkers, and histopathology data	Personalised surveillance protocols, early recurrence detection, treatment optimisation.

Studies evaluating digital twin-guided surgery report enhanced surgical precision, reduced operative time in experienced hands, and potential for improved functional outcomes [38]. Technology particularly benefits training scenarios, allowing novice surgeons to practise complex procedures in realistic virtual environments before progressing to patient care [8,25].

Biomechanical simulation capabilities within digital twins enable the prediction of tissue deformation during surgery, addressing challenges in image-guided intervention [39]. Digital-twin-based biomechanical models for prostate brachytherapy can simulate the impact of catheter insertion on prostate deformation and geometry, enabling planning strategies that compensate for tissue displacement and support more accurate high–dose-rate treatment delivery [11,40]. Extended reality technologies such as virtual and augmented reality enhance the usefulness of surgical digital twins by offering immersive 3D visualisation and intuitive interaction with patient-specific virtual models during planning, simulation, and training. Haptic feedback integrated into virtual and extended reality surgical simulators can improve training and procedural execution by providing force and tactile sensations that approximate interactions with soft tissues and other anatomical structures [41,42].

5. Functional urology applications

Digital twin technology extends beyond oncological and surgical applications to address functional urological disorders. The bladder digital twin represents a pioneering effort to model the bladder's complex function under both physiological and pathological conditions. This computational model integrates biomechanical properties, neural control mechanisms, and cellular-level processes to simulate bladder behaviour in health and disease [27]. For bladder outlet obstruction, digital twins through simulation predict potential responses to pharmacological and surgical interventions. The model accounts for structural changes in bladder wall composition, altered contractility, and compensatory mechanisms, enabling personalised treatment selection.

Lower urinary tract symptoms represent another application domain for digital twin technology. Patient-specific models incorporating urodynamic data, imaging findings, and symptom assessments simulate bladder and urethral function throughout voiding cycles [27,43]. These simulations identify underlying pathophysiological mechanisms contributing to symptoms, guiding targeted therapeutic interventions. For neurogenic bladder dysfunction, digital twins may facilitate optimisation of intermittent catheterisation schedules, medication regimens, and neuromodulation parameters based on individual patient physiology [27].

Male infertility evaluation and treatment planning may benefit from digital twin approaches modelling reproductive physiology. Virtual models integrating hormonal profiles, testicular imaging, semen analysis, and genetic factors could simulate responses to fertility treatments, predict success rates, and optimise intervention strategies. While these applications remain largely theoretical, preliminary work establishing computational frameworks provides a foundation for future development [44–47]. The complexity of reproductive physiology poses significant modelling challenges, requiring the integration of multiple biological scales, from molecular signalling to organ-level function [45,46].

6. Artificial intelligence integration

The synergy between digital twin technology and artificial intelligence amplifies capabilities beyond what either approach can achieve independently. Machine learning algorithms process vast datasets to identify patterns, predict outcomes, and refine model parameters, with efficiency exceeding that of traditional computational methods [48]. Deep learning architecture automatically extracts relevant features from medical imaging, enabling accurate tumour segmentation, tissue characterisation, and anatomical reconstruction for the creation of digital twins [49]. Natural language processing facilitates the extraction of relevant information from electronic health records, clinical notes, and pathology reports, enriching the foundations of digital twins.

Artificial intelligence enhances digital twin predictive capabilities through sophisticated pattern recognition and forecasting algorithms. In prostate cancer management, machine learning models trained on large patient cohorts predict individual disease trajectories by identifying subtle patterns in imaging and clinical data [15,19]. These predictions inform digital twin simulations, enabling more accurate forecasting of tumour growth, metastatic risk, and treatment response [16]. Reinforcement learning approaches optimise treatment strategies by simulating multiple therapeutic scenarios and identifying pathways maximising desired outcomes while minimising adverse effects.

Real-time artificial intelligence integration enables dynamic updates to the digital twin during surgical procedures or simulated learning [50]. Computer vision algorithms process intraoperative imaging streams, automatically updating digital twin representations to reflect current anatomical states. This continuous refinement enhances navigation accuracy and compensates for tissue deformation, patient movement, and evolving surgical fields [7,11]. Explainable artificial intelligence approaches address concerns regarding algorithmic transparency by providing interpretable rationales for predictions and recommendations, fostering clinical trust and facilitating regulatory approval. As shown in Fig. 2, current urological digital twin efforts converge on three main clinical domains: uro-oncology, surgical planning, and functional urology.

Table 2 presents the key artificial intelligence technologies employed in urological digital twin development, their specific applications, and the advantages they provide for enhancing model functionality and clinical utility.

7. Challenges and implementation barriers

7.1. Technical challenges

Digital twin implementation in urology faces substantial technical challenges that impede widespread clinical adoption. Computational complexity represents a primary obstacle, as real-time simulation of biological processes requires significant processing power and sophisticated algorithms [51,52]. High-performance computing infrastructure, necessary for maintaining model accuracy and enabling dynamic updates, remains financially prohibitive for many healthcare institutions. Data integration presents another critical challenge, as digital twins require seamless aggregation of heterogeneous data from electronic health records, imaging systems, laboratory information systems, and wearable devices. Lack of standardised data formats, interoperability issues between systems, and incomplete data capture compromise model completeness and accuracy. Model validation poses significant methodological challenges in digital twin development. Establishing ground truth for complex biological simulations proves difficult, particularly for predictions of future events or untested interventions [44,53]. Prospective clinical validation studies, while essential for demonstrating clinical utility, require substantial resources, long follow-up periods, and careful study design. Uncertainty quantification remains an active research area, with the need for robust methods to characterise prediction confidence and communicate uncertainty to clinicians. Model calibration for individual patients requires efficient parameter-estimation techniques that can operate with limited patient-specific data while avoiding overfitting.

7.2. Data privacy and security

The data-intensive nature of digital twins raises significant privacy and security concerns. Patient-specific models require extensive personal health information, genomic data, and continuous physiological

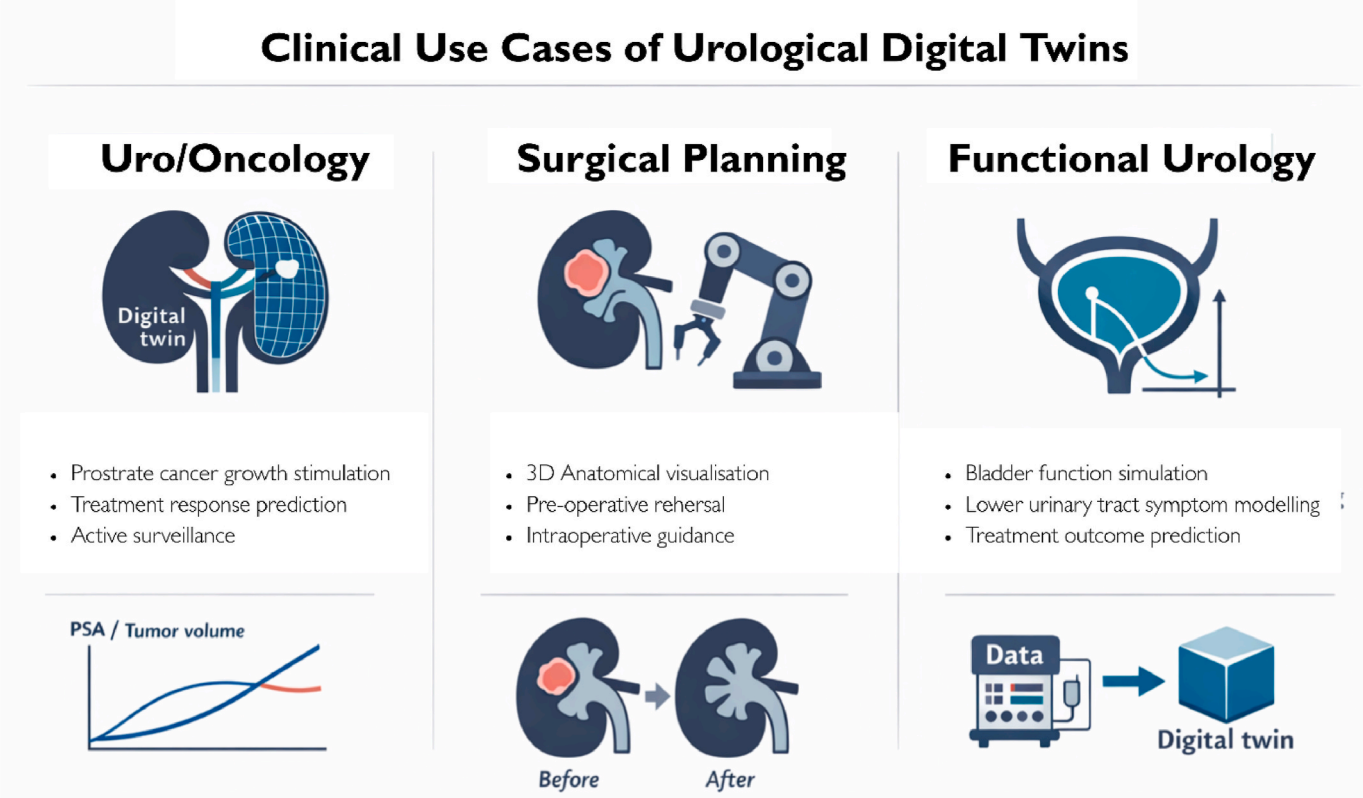

Fig. 2. Simplified overview of core clinical use cases for urological digital twins, including uro-oncological decision support, surgical planning and guidance, and functional urology applications. The figure complements Sections 3–6 by emphasising practical, patient-facing scenarios rather than technical implementation detail.

Table 2
Artificial intelligence technologies in urological digital twins.

AI Technology	Digital Twin Application	Key Advantages
Deep Learning Segmentation [48]	Automated anatomical structure identification, tumour delineation, organ reconstruction	Reduced manual segmentation time, improved accuracy, and standardisation across cases
Machine Learning Prediction Models [15,19]	Disease progression forecasting, treatment response prediction, outcome estimation	Enhanced predictive accuracy, pattern recognition in complex data, personalised risk stratification
Natural Language Processing [48,49]	Clinical data extraction from records, automated documentation analysis, information synthesis	Comprehensive data integration, reduced manual data entry, improved information completeness
Computer Vision [7,11]	Real-time intraoperative model updating, tissue texture recognition, and surgical navigation enhancement	Dynamic model adaptation, improved surgical guidance, and compensation for tissue deformation
Reinforcement Learning [16,48,49]	Treatment protocol optimisation, decision support, parameter tuning for model calibration	Automated strategy optimisation, learning from outcomes, and continuous improvement capability

monitoring, creating substantial privacy risks. Regulatory frameworks, including the General Data Protection Regulation, impose strict requirements for data handling, storage, and processing that digital twin systems must satisfy [54]. Ensuring data security against breaches, unauthorised access, and cyberattacks demands robust cybersecurity measures and continuous monitoring. The potential for patient re-identification from supposedly anonymised digital twin data necessitates careful consideration of de-identification strategies and access controls [55,56].

Ethical considerations extend beyond privacy to encompass questions of digital twin ownership, control, and use. Determining whether patients own their digital twins, have the right to access and modify them, or can request their deletion raises novel ethical and legal questions. Information-consent processes must adequately explain digital twin technology, its uses, risks, and benefits to patients who may lack technical understanding [54,55,57]. The potential for digital twins to reveal sensitive health predictions that patients may prefer not to know requires careful consideration of disclosure policies and patient autonomy.

7.3. *Regulatory and standardisation issues*

Regulatory uncertainty surrounding digital twin technology complicates clinical translation. Existing regulatory frameworks were not designed for adaptive, continuously updating computational models that blur the boundaries between medical devices, clinical decision-support tools, and diagnostic systems [57]. Classification of digital twins within regulatory categories determines approval pathways, post-market surveillance requirements, and liability considerations. The lack of established regulatory precedent creates uncertainty for developers and healthcare institutions considering implementing digital twins [52,54,58].

Standardisation across digital twin development methodologies, data formats, and validation approaches remains absent. Heterogeneity in technical approaches, modelling frameworks, and clinical applications prevents comparison across studies and hampers knowledge synthesis. Development of consensus guidelines for digital twin creation, validation, and reporting would facilitate quality assessment, reproducibility, and clinical adoption. Professional societies and regulatory bodies have begun addressing these gaps, but comprehensive standards

are yet to be forthcoming [4,52].

7.4. Clinical integration and workflow

Integrating digital twin technology into existing clinical workflows presents practical challenges. Clinician training requirements, time demands for model interaction, and potential workflow disruption must be carefully managed. User-interface design critically influences clinical adoption, requiring intuitive visualisation and interaction capabilities that busy clinicians can easily utilise [59,60]. The steep learning curve associated with complex technologies may deter adoption, particularly among practitioners uncomfortable with advanced computational tools.

Resource requirements for digital twin implementation extend beyond technology to include multidisciplinary expertise in clinical medicine, computational modelling, data science, and software engineering [52,60]. Establishing multidisciplinary teams for digital twin development requires sustained institutional commitment, including dedicated funding for salaries, training, and infrastructure [52]. Cost-benefit analyses for medical digital twins must demonstrate clear value through quantifiable improvements in patient outcomes, such as reduced complication rates or better long-term survival, alongside operational gains like shorter hospital stays or optimised resource allocation [52,60]. Such analyses typically project ROI via metrics including reduced readmissions, lower per-case costs from precision interventions, and efficiency from streamlined workflows, helping offset high upfront investments in development and infrastructure [51,52]. Economic models in digital health suggest the possibility of cost offsets over time [48], but robust urology-specific cost-effectiveness data are currently lacking.

8. Future directions and research priorities

Future developments in urological digital twins will likely emphasise several key directions. Enhanced integration with wearable devices and continuous-monitoring technologies will enable more dynamic model updates and real-time health tracking [61,62]. The proliferation of Internet-of-Medical-Things devices offers unprecedented opportunities to capture physiological data, though challenges in data quality, calibration, and standardisation require attention [61,62]. The development of federated-learning approaches may enable collaborative model development across institutions while preserving patient privacy, thereby addressing current limitations in single-institution datasets [63,64].

Expansion beyond oncological and surgical applications to encompass broader urological conditions represents another priority. Digital twins for urolithiasis could predict stone-formation risk, simulate fragmentation patterns for different lithotripsy modalities, and optimise preventative strategies [65]. For benign prostatic hyperplasia, models integrating prostate morphology, urodynamics, and symptom profiles could guide treatment selection between medical management, minimally invasive procedures, and surgery [66]. Paediatric urology applications, including the management of vesicoureteral reflux and planning for hypospadias repair, warrant exploration [67].

Integration of multi-omics data, including genomics, transcriptomics, proteomics, and metabolomics, will enhance the digital twin's biological fidelity and predictive capabilities [4]. System biology approaches that model molecular pathways, cellular interactions, and tissue-level phenomena promise a more mechanistic understanding of disease processes [52]. Personalised medicine will benefit from digital twins capable of predicting individual responses to targeted therapies based on molecular profiles. The development of population-level digital twins that aggregate individual models could inform public health initiatives, resource allocation, and healthcare policy decisions [68].

Standardisation efforts must prioritize the development of consensus methodologies for the creation, validation, and reporting of digital twins [69,70]. Establishing benchmark datasets, reference implementations, and validation frameworks would facilitate comparisons across approaches and accelerate progress. International collaboration through professional societies and research consortia can coordinate standardisation efforts and promote best practices. Regulatory engagement remains critical to clarify approval pathways, establish safety and efficacy standards, and provide guidance for developers and clinicians [4,64,71].

Clinical validation studies increasingly indicate that digital twin-enabled interventions can support improvements in patient outcomes, decision-making quality, and healthcare efficiency when evaluated against real-world clinical data, representing a critical benchmark for assessing digital twin utility [68,72]. To establish robust clinical value, randomised, pragmatic, or hybrid comparative study designs, integrating real-world evidence with in-silico or digital-twin-augmented cohorts are increasingly recognised as essential complements to conventional randomised controlled trials. Furthermore, long-term observational and implementation studies are required to evaluate the sustainability, scalability, and adaptive evolution of digital twin systems within real-world clinical workflows, informing deployment strategies and identifying areas for iterative refinement and standardisation.

9. Limitations of the review

This narrative review has several limitations that warrant acknowledgement. The rapidly evolving nature of digital twin technology means that recent developments may not be fully captured, and the landscape will continue changing during the publication process. The heterogeneity of studies, methodologies, and applications precluded formal quality assessment and meta-analysis, limiting quantitative synthesis of findings. Publication bias favouring positive results may lead to overestimating digital twin capabilities and underrepresenting failed implementations or negative findings.

The review focused on English language publications, potentially excluding relevant work published in other languages. Geographic and institutional biases in literature may affect the generalisability of findings across diverse healthcare settings and patient populations. The nascent state of digital twin implementation in urology means that much of the reviewed evidence comes from pilot studies, feasibility assessments, and technical validation rather than large-scale clinical trials demonstrating patient benefit. Long-term outcomes, cost-effectiveness, and real-world implementation experiences remain insufficiently studied.

The narrative synthesis approach, while appropriate for the heterogeneous literature base, introduces potential for subjective interpretation and selection bias in highlighting particular findings. Alternative systematic review methodologies may have identified different themes or reached alternative conclusions. The review does not provide detailed technical specifications or implementation guidelines, as these vary substantially across applications and require specialised expertise. Readers seeking to implement digital twin technology should consult primary literature, technical documentation, and domain experts for specific guidance.

10. Conclusion

Digital twin technology represents a transformative advancement in urological practice, offering unprecedented capabilities for personalised diagnosis, treatment planning, and outcome prediction. Applications in uro-oncology demonstrate promise, with patient-specific tumour growth simulation, surgical navigation enhancement, and treatment response forecasting showing clinical utility. Integration with artificial intelligence amplifies digital twin capabilities, enabling sophisticated pattern recognition, predictive modelling, and real-time adaptation. The technology extends beyond oncological applications to functional urology, surgical training, and healthcare system optimisation.

Despite compelling potential, substantial barriers impede

widespread clinical implementation. Technical challenges, including computational complexity, data integration difficulties, and validation requirements, demand continued research and development. Ethical considerations regarding privacy, consent, and digital twin ownership require careful deliberation and policy development. Regulatory uncertainty and the absence of standardised approaches complicate clinical translation. Resource intensiveness and the need for multidisciplinary expertise present practical obstacles for many institutions.

Successful digital twin implementation in urology will require collaborative efforts among clinicians, researchers, technology developers, regulators, and patients. Priorities include rigorous clinical validation through well-designed studies, development of standardised methodologies and reporting frameworks, engagement with regulatory agencies to establish clear approval pathways, and demonstration of value through improved outcomes and efficiency. Educational initiatives preparing current and future urologists to utilise digital twin technology effectively will facilitate adoption.

The trajectory of digital twin technology in urology appears promising, with ongoing advancements in computational power, artificial intelligence, and data integration capabilities continually enhancing feasibility. As technical challenges are addressed, ethical frameworks are established, and clinical value is demonstrated, digital twins may transition from a research curiosity to a standard clinical tool. The vision of truly personalised, predictive, and preventative urological care enabled by digital twin technology moves progressively closer to reality. Continued investment in research, development, and validation will determine the pace and extent of this transformation, ultimately benefiting patients through more precise, effective, and individualised urological care.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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