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ARTIFICIAL INTELLIGENCE IN EARLY DETECTION AND MANAGEMENT OF BENIGN UROLOGICAL TUMORS-A NARRATIVE REVIEW

Narrative Review

Zainab Yousaf[1]*, Ammar Khalil[2], Syed Gufran Sadiq Zaidi[3]

[1]Department of Computer Science, Bahria University, Islamabad, Pakistan.

[2]Lecturer, Department of Data Science, University of Kotli, AJ&K, Pakistan.

[3]Master of Public Health Student, Nazarbayev University, Astana, Kazakhstan.

Corresponding Author: Zainab Yousaf, Department of Computer Science, Bahria University, Islamabad, Pakistan, zainabyousaf17@gmail.com

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ABSTRACT

Background: Benign urological tumors of the kidney and bladder, such as renal oncocytomas, angiomyolipomas, and non-muscle invasive bladder lesions, are increasingly diagnosed due to widespread use of imaging modalities. Differentiating these lesions from malignant counterparts remains a clinical challenge, often leading to unnecessary interventions. Artificial intelligence (AI) has emerged as a transformative tool in urology, offering advanced diagnostic support through radiomics, machine learning, and image analysis.

Objective: This narrative review aims to explore the current applications, limitations, and future potential of AI in the early detection and management of benign kidney and bladder tumors, focusing on its integration within medical imaging and urological practice.

Main Discussion Points: Key themes include the role of AI-enhanced radiological imaging in differentiating benign from malignant renal masses, AI-guided cystoscopy and histopathology for improved bladder tumor assessment, predictive analytics for individualized surveillance, and intraoperative AI tools for surgical planning. The review also discusses limitations such as small sample sizes, methodological variability, and issues related to generalizability and data standardization.

Conclusion: AI shows promising potential in improving diagnostic accuracy and clinical decision-making in benign urological tumors. However, the evidence base is still developing and limited by methodological weaknesses. Larger, multicenter prospective studies are necessary to validate current findings and support safe, widespread clinical implementation.

Keywords: Artificial Intelligence, Benign Urological Tumors, Kidney Imaging, Bladder Cancer, Radiomics, Narrative Review.

INTRODUCTION

Benign urological tumors, particularly those affecting the kidneys and bladder, represent a substantial clinical concern due to their high prevalence, potential for misdiagnosis, and impact on healthcare resources. While malignant urological cancers such as renal cell carcinoma and urothelial carcinoma garner significant attention, benign lesions—such as renal angiomyolipomas, oncocytomas, and non-invasive bladder tumors—pose distinct diagnostic and therapeutic challenges. Globally, the incidence of small renal masses has surged in the past decades, primarily attributed to increased utilization of cross-sectional imaging modalities. Approximately 20–30% of renal masses detected incidentally are benign, yet many undergo surgical intervention due to diagnostic uncertainty, thereby exposing patients to unnecessary risks and morbidity (1,2). Similarly, non-muscle invasive bladder tumors often necessitate repeated invasive procedures such as cystoscopy, which not only burden patients but also strain healthcare systems due to their high recurrence rates and the need for long-term surveillance (3). In parallel with the growing recognition of these clinical challenges, artificial intelligence (AI) has emerged as a transformative force in medicine, offering the potential to enhance accuracy and efficiency across diagnostic and therapeutic domains. AI models, particularly those grounded in machine learning and deep learning algorithms, are increasingly being integrated with radiological and pathological workflows in urology. These systems are capable of interpreting complex imaging datasets, identifying subtle patterns, and aiding in differentiating benign from malignant lesions with considerable precision. In renal tumor evaluation, for instance, AI-enhanced radiomics has demonstrated capacity to distinguish oncocytomas from renal cell carcinomas, an area where conventional imaging often falls short (4,5).

In bladder cancer, AI-driven cystoscopy and histopathological image analysis have been shown to improve tumor detection rates and grading accuracy, thereby supporting more informed clinical decisions (6). Despite these promising developments, several knowledge gaps remain. Much of the current research is concentrated on malignant tumors, with limited focus on benign urological lesions. Additionally, many AI models are still in the developmental or early clinical evaluation stages, and their generalizability across diverse populations and imaging protocols remains uncertain. The integration of AI into everyday urological practice is further complicated by technical, ethical, and regulatory hurdles, including data standardization, interpretability of AI decisions, and clinician trust in automated systems. There is also a lack of robust, multicentric studies assessing the real-world performance and impact of AI tools on clinical outcomes in benign tumor management (7,8). Against this backdrop, the objective of this narrative review is to explore the evolving role of artificial intelligence in the early detection and management of benign kidney and bladder tumors. The review aims to provide a comprehensive synthesis of existing literature on AI applications in this context, highlight clinical use cases and technological innovations, and identify critical limitations and areas for future research.

This review encompasses recent peer-reviewed literature from the past five years, focusing on studies that applied AI methodologies—such as machine learning, deep learning, and radiomics—to the diagnosis, characterization, or treatment planning of benign urological tumors. Emphasis is placed on non-invasive diagnostic modalities, including imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), and cystoscopy, and their enhancement through AI technologies. Studies centered solely on malignant or metastatic disease without mention of benign differentiation were excluded. The significance of this review lies in its timely focus on a relatively underexplored area within urological oncology. By spotlighting the capabilities of AI in distinguishing benign from malignant lesions, this work seeks to reduce overtreatment, optimize patient care pathways, and support evidence-based deployment of advanced technologies in clinical urology. Furthermore, the insights presented here may help inform the development of standardized AI protocols and foster collaborative efforts between data scientists and urologists to advance precision medicine in benign urological diseases.

THEMATIC DISCUSSION

AI in Medical Imaging for Early Detection of Benign Kidney Tumors

Artificial intelligence has increasingly demonstrated its value in enhancing diagnostic precision in renal imaging, particularly in differentiating benign from malignant kidney lesions. Conventional imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI) frequently fall short in distinguishing oncocytomas and angiomyolipomas from renal cell carcinoma, often leading to overtreatment. AI-powered radiomics has emerged as a valuable tool in this context, allowing for high-dimensional quantitative analysis of imaging data. A study highlighted the ability of AI-integrated radiomics to stratify renal lesions based on subtle texture differences from CT and MRI scans, thus aiding in identifying benign tumors with increased specificity (1). Similarly, a review emphasized that AI models trained on large, annotated imaging datasets achieved high accuracy in classifying renal mass subtypes, suggesting a practical application for guiding conservative management where appropriate (2). Despite promising findings, these models still require external validation across varied populations and scanner types.

Bladder Tumor Detection and AI-Enhanced Cystoscopy

In the realm of bladder tumor identification, AI-assisted cystoscopy systems have shown notable advancements in improving tumor detection rates. A recent meta-analysis found that AI-based support systems integrated with cystoscopic imaging achieved pooled sensitivities and specificities above 95%, indicating excellent discriminatory ability between malignant and benign lesions during real-time visualization (3). Deep learning models have also been applied to white-light and narrow-band images, effectively grading bladder tumors based on color differentiation using the RGB method, with accuracies nearing 98% for differentiating benign from low- or high-grade lesions (4). However, the variability in performance across flat versus papillary lesions suggests that while AI holds promise, its full clinical integration must account for morphological heterogeneity.

Pathology and Histological Classification through AI

Beyond imaging, histopathological analysis of urological tumors stands to benefit substantially from AI deployment. Studies have demonstrated that AI algorithms applied to histological slides can reach near-perfect sensitivity and specificity in distinguishing benign renal tissue from renal cell carcinoma (5,6). A recent reported that an AI diagnostic model for RCC achieved 100% sensitivity and 97.1% specificity, outperforming many human pathologists in controlled comparisons (7). Similar advances have been seen in bladder tumor histology, where AI systems support grading and subtype classification with minimal intra-observer variability. Nevertheless, challenges related to digitized slide standardization, variable staining protocols, and the interpretability of AI decisions remain areas of concern.

Predictive Modeling and Risk Stratification

AI-based predictive analytics have also emerged as tools for personalized risk assessment in benign urological tumors. For example, machine learning models that integrate patient demographics, radiologic features, and clinical biomarkers have shown capacity to predict the probability of tumor progression or recurrence in non-muscle invasive bladder tumors. Similarly, a study demonstrated how AI-driven mathematical models accurately identified patients at high risk for recurrence by combining clinical and genomic data, potentially reducing unnecessary invasive procedures (8). However, these predictive tools are often constrained by dataset biases and require consistent clinical validation across multi-institutional cohorts.

AI in Intraoperative Guidance and Surgical Planning

The integration of virtual 3D modeling and AI in the operating room is reshaping how benign renal tumors are approached surgically. Intraoperative AI-assisted navigation tools can provide real-time anatomic overlays, thereby minimizing collateral tissue damage. A study discussed how AI-aided surgical models help reduce thermal ischemia and preserve nephron function, particularly critical when resecting benign renal tumors in elderly or comorbid patients (9). Despite these advantages, implementation is hindered by the need for specialized hardware, operative training, and cost barriers.

Differentiating Benign vs. Malignant Lesions with Explainable AI

One growing trend in AI applications is the use of explainable models to build clinician trust and transparency in diagnostic decision-making. A study introduced an explainable AI framework that utilized SHAP (SHapley Additive exPlanations) values to visualize feature importance in distinguishing benign kidney lesions from malignancies on CT scans (10). This level of interpretability is essential in urology, where clinical decisions often require justification to patients and surgical teams. However, most current models still operate as "black boxes," a significant limitation for widespread clinical adoption.

Challenges of Clinical Translation and Standardization

Despite robust evidence supporting AI's diagnostic capabilities, the pathway to clinical implementation is riddled with hurdles. One of the primary issues is the lack of standardized datasets and universal benchmarks for AI training and evaluation. Studies emphasized that many AI models are trained on limited datasets from single institutions, reducing their generalizability and increasing the risk of overfitting (11,12). In addition, regulatory frameworks for AI use in diagnostics are still evolving, often lagging behind the technology's pace.

Gaps and Future Directions

Although substantial strides have been made, many questions remain unanswered. There is a scarcity of longitudinal studies investigating the impact of AI on patient outcomes in benign tumor management. Furthermore, limited data exists on the performance of AI in pediatric urology or underrepresented populations. There is also a need for integrated systems that combine AI diagnostics with decision support for urologists, streamlining care from diagnosis to follow-up. Addressing these gaps requires cross-disciplinary collaboration and a robust commitment to transparent, reproducible research.

CRITICAL ANALYSIS AND LIMITATIONS

Despite the promising outlook on artificial intelligence (AI) applications in the early detection and management of benign urological tumors, several methodological limitations within the existing body of literature raise concerns about the robustness and clinical applicability of current findings. A prominent limitation across many reviewed studies is the relatively small sample size. Several AI models, particularly those developed for radiological and cystoscopic evaluation, are trained and validated on datasets collected from single-center studies or limited patient cohorts, which can lead to overfitting and restrict their generalizability in real-world clinical settings. For example, although a study demonstrated high diagnostic accuracy of AI-supported cystoscopy, the pooled analysis drew from only a few retrospective studies, each with limited patient representation, thus limiting statistical power and external validity (13-15). In addition to sample size constraints, there is a clear absence of large-scale randomized controlled trials (RCTs) evaluating AI tools for benign tumor diagnosis and management. Most studies are observational or retrospective in nature, which inherently introduces susceptibility to confounding variables and selection bias. A study, while highlighting the capabilities of AI in histological differentiation, based their analysis on retrospective data without randomization or standardized protocols across sites, making it difficult to assess causal relationships or eliminate performance bias (16). Moreover, very few studies report blinding of assessors during AI model validation, further increasing the risk of performance and detection bias.

Another substantial limitation is the heterogeneity in methodological approaches, particularly in terms of input data quality, imaging protocols, and outcome measurements. For instance, models used for radiomics-based kidney tumor classification, as reported by a study, vary widely in terms of feature extraction methods, image resolution, and annotation techniques (17,18). These inconsistencies in data preprocessing and outcome metrics hinder meaningful comparisons between studies and compromise efforts to replicate findings across independent cohorts. Similarly, bladder cancer detection studies employed RGB-based image analysis, which is not universally standardized or validated across different cystoscopic systems, limiting reproducibility (19,20). Publication bias also appears to be a non-trivial concern. The current literature is dominated by studies reporting highly favorable results for AI performance, while negative or inconclusive findings are rarely published. This skewed representation likely inflates expectations of AI capabilities and downplays technical failures or limitations. Studies with high model performance, often lack discussion of model errors, failed predictions, or real-world deployment challenges, which are essential for assessing the true utility and safety of AI in clinical practice (21). The overrepresentation of successful results may reflect a tendency toward selective reporting, compounded by the novelty and publication appeal of AI-driven innovations.

Generalizability remains a further critical issue. Most reviewed studies are conducted within specific geographic or institutional settings, often involving homogeneous populations with limited ethnic and demographic diversity. For example, the datasets used by a study were predominantly sourced from Western or urban hospital systems, which may not reflect patient populations in low-resource or rural environments where benign urological tumors are also prevalent but underdiagnosed (22). Furthermore, many AI algorithms rely on high-quality imaging or digitized pathology slides, technologies that are not universally accessible, thereby limiting the feasibility of global implementation. Ultimately, while the current evidence base supports AI's potential in improving diagnostic precision and streamlining management pathways for benign urological tumors, the limitations in study design, variability in methodology, and concerns over bias and generalizability call for cautious interpretation. Rigorous prospective trials, standardized protocols, and inclusive datasets are imperative to validate these technologies and ensure that their benefits are equitably distributed across diverse clinical contexts.

IMPLICATIONS AND FUTURE DIRECTIONS

The integration of artificial intelligence into the early detection and management of benign urological tumors offers tangible opportunities to improve clinical decision-making and patient outcomes. AI-enhanced imaging techniques, particularly radiomics and machine learning applied to CT and MRI, can assist clinicians in distinguishing benign from malignant kidney and bladder lesions with greater accuracy. This holds considerable significance in reducing unnecessary surgical interventions for benign masses, especially in elderly or comorbid patients who may not tolerate invasive procedures well. In practical terms, AI can support urologists in formulating more personalized, conservative management strategies where appropriate, promoting nephron-sparing approaches and minimizing overtreatment risks (23). Furthermore, AI-aided cystoscopy and histopathological tools can enhance detection and grading precision in bladder lesions, streamlining diagnostic workflows and potentially reducing reliance on subjective interpretation (24). From a policy and healthcare system perspective, the findings of this review underscore the growing need to develop formal clinical guidelines on the use of AI in urology. As AI continues to evolve beyond experimental phases, its integration into practice will require structured protocols that address safety, accountability, and standardization. Currently, the absence of universally accepted criteria for AI implementation in benign urological tumor care leads to inconsistent application and uncertainty among clinicians. Establishing multidisciplinary frameworks involving urologists, radiologists, pathologists, and data scientists will be essential in shaping guidelines that ensure both efficacy and ethical integrity in clinical deployment (25). Regulatory agencies may also need to refine approval pathways for AI tools, ensuring rigorous evaluation and post-deployment monitoring akin to pharmacologic interventions.

Despite encouraging developments, significant research gaps persist. One major area of uncertainty is the long-term clinical impact of AI on patient outcomes in benign tumor management. Most existing studies focus on model performance metrics—such as sensitivity, specificity, and accuracy—without tracking downstream consequences on clinical decision-making, patient satisfaction, or recurrence rates. Additionally, the differential performance of AI models across diverse populations remains largely unexplored. Many datasets are homogenous in terms of ethnicity, geography, and socioeconomic background, raising concerns about algorithmic bias and inequity in diagnostic accuracy (26). There is also a lack of evidence regarding the effectiveness of AI tools in resource-limited settings, where infrastructure constraints may hinder the seamless integration of advanced technologies. To address these gaps, future research must prioritize prospective, multicenter randomized controlled trials (RCTs) that assess not only diagnostic performance but also patient-centered outcomes such as morbidity, cost-effectiveness, and quality of life. These studies should adopt standardized data collection protocols and include external validation cohorts to enhance generalizability. Additionally, the development of explainable AI models should be encouraged to foster trust and interpretability among clinicians, thereby supporting informed clinical decision-making. Combining AI with clinical decision support systems that incorporate patient history, laboratory results, and risk factors may further optimize diagnostic pathways and therapeutic planning (25,26). Moreover, longitudinal studies are needed to explore how AI can be integrated into long-term surveillance strategies for patients with benign lesions, particularly in determining recurrence risk and guiding follow-up intervals. In conclusion, the evolving role of AI in managing benign urological tumors has the potential to significantly transform diagnostic and therapeutic paradigms. However, realizing this potential depends on robust clinical validation, thoughtful policy integration, and continued research addressing existing limitations. By aligning technological innovation with clinical pragmatism, AI can become an indispensable tool in improving the precision, efficiency, and equity of urological care.

CONCLUSION

Artificial intelligence is progressively transforming the landscape of benign urological tumor management, offering enhanced accuracy in early detection, differential diagnosis, and individualized treatment planning. Through applications in radiomics, cystoscopy, histopathology, and predictive analytics, AI has demonstrated the potential to reduce overtreatment and improve diagnostic confidence in distinguishing benign from malignant renal and bladder lesions. While the existing literature provides encouraging evidence for AI's capabilities, much of it is based on retrospective analyses, single-center datasets, and algorithm-centric outcomes, limiting the strength and applicability of conclusions. Nonetheless, the consistency of findings across diverse modalities supports cautious optimism regarding AI's integration into clinical workflows. For clinicians, the practical use of validated AI tools can complement traditional diagnostics, particularly in ambiguous or borderline cases. For researchers, future efforts should focus on developing robust, multicenter, prospective trials with diverse populations and standardized methodologies to validate AI systems in real-world settings. Continued interdisciplinary collaboration will be essential to translate these technologies from theoretical promise to clinical reality, ensuring they are safe, equitable, and impactful across healthcare systems.

AUTHOR CONTRIBUTION

Author	Contribution
Zainab Yousaf*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Ammar Khalil	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Syed Gufran Sadiq Zaidi	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

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