

ORIGINAL RESEARCH ARTICLE

Design and implementation of the DmgCDSS framework: Toward transparent benign prostatic hyperplasia clinical decision support

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Abstract

Transparent and guideline-compliant clinical decision support systems (CDSSs) are essential for trustworthy digital health. However, numerous rule-based systems lack explicit provenance, interoperability, and explainability. This study aims to design and evaluate DmgCDSS, a transparent, modular CDSS framework for benign prostatic hyperplasia (BPH) that supports guideline-based reasoning, provenance tracking, and interoperability through structured data and open standards. Clinical recommendations from major BPH guidelines (European Association of Urology, American Urological Association, National Institute for Health and Care Excellence) were encoded as modular JavaScript Object Notation rule objects with versioning and metadata. A forward-chaining inference engine, implemented in C#, processes patient data mapped to standard terminologies (Systematized Nomenclature of Medicine–Clinical Terms, Logical Observation Identifiers Names and Codes, International Classification of Diseases, 10th Revision). System outputs include actionable recommendations with traceable rule sources. Performance was evaluated through case-based concordance testing on ten published BPH case reports. Agreement between DmgCDSS and reference recommendations was assessed across diagnosis, risk stratification, investigation, and treatment domains. DmgCDSS achieved an overall concordance of 80% (32/40 domain-level decisions) with guideline-based reference outputs. Discrepancies were mainly due to missing clinical details or evolving recommendations. Rule evaluation completed within 1 s per case. The framework supports interoperability through Fast Healthcare Interoperability Resources-compatible data structures and explainable output logs. DmgCDSS demonstrates the technical feasibility of a transparent, guideline-based CDSS for BPH. The framework enables reproducible rule management, traceable recommendations, and standards-based interoperability. Broader validation using electronic health records and clinician usability testing is planned to confirm clinical utility.

Keywords: Clinical decision support system; Benign prostatic hyperplasia; Lower urinary tract symptoms; Rule-based reasoning; Treatment planning; Explainable artificial intelligence; Life expectancy estimation

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1. Introduction and clinical significance

The need for transparent, auditable decision support in urology is critical, particularly where diagnostic ambiguity leads to management variability and potential overtreatment. This challenge is starkly illustrated in prostate cancer (PCa) diagnostics, where prostate-specific antigen (PSA) screening suffers from low specificity, contributing to overdiagnosis, unnecessary biopsies, and increased healthcare costs. The DmgCDSS framework addresses a parallel clinical problem: the complex, symptom-driven management of benign prostatic hyperplasia (BPH). Transparent CDSS systems are uniquely positioned to help reduce this management uncertainty. Clinical decision support systems (CDSSs) are designed to augment medical decision-making by combining patient-specific data with structured clinical knowledge to generate recommendations at the point of care.¹ Despite their recognized potential to enhance quality, reduce variation, and improve adherence to evidence-based guidelines, numerous CDSSs remain underused. Barriers include opaque reasoning processes, difficulties in updating with new evidence, lack of interoperability, and limited integration into electronic health record (EHR) environments.^{2,3}

In urology, BPH represents one of the most prevalent chronic conditions affecting ageing men, with lower urinary tract symptoms (LUTSs) imposing a substantial burden on daily life and health systems. Management requires a nuanced assessment of symptom severity, comorbidities, and treatment suitability, alongside careful monitoring of disease progression and complications.^{4,5} International guidelines from the European Association of Urology (EAU),⁶ the American Urological Association (AUA),⁷ and the National Institute for Health and Care Excellence (NICE)⁸ provide evidence-based frameworks for BPH care. However, applying these recommendations consistently in practice can be challenging, particularly in busy outpatient environments where decision complexity is high and guideline updates are frequent.

Existing decision support tools in this field are predominantly patient-facing decision aids, developed to support shared decision-making by clarifying treatment choices, risks, and benefits.^{9,10} While these aids improve patient knowledge and decisional confidence, they typically do not integrate dynamically with clinical workflows, nor do they offer clinician-facing, explainable reasoning processes. Furthermore, most of them lack mechanisms for systematic updating or interoperability with standardized health information technology infrastructures.

The present study introduces DmgCDSS, a modular, explainable, and guideline-aligned CDSS specifically

designed for BPH. Its framework encodes international guideline recommendations into a transparent rule base, operationalized through a forward-chaining inference engine and supported by provenance tracking, interoperability standards, and extensibility for probabilistic reasoning. We evaluate the feasibility and accuracy of DmgCDSS using case-based validation against published reports of BPH management. In doing so, we aim to demonstrate both the technical feasibility of transparent CDSS in urology and its potential clinical value in improving care consistency.

Benign prostatic hyperplasia is a progressive and highly prevalent condition among older men, often associated with bothersome urinary symptoms, impaired quality of life, and risks of complications, such as urinary retention, bladder stones, and hydronephrosis. Clinical decisions in this domain are inherently complex, requiring integration of symptom scores, prostate size, comorbidity burden, and patient preferences. Inconsistent interpretation of guidelines or variability in practice may result in delayed treatment, unnecessary interventions, or inappropriate selection of therapy.

A transparent and modular CDSS, such as DmgCDSS, directly addresses these challenges by translating evidence-based recommendations into explainable, patient-specific outputs. Unlike black-box algorithms, it makes reasoning steps and source citations explicit, thereby supporting clinician trust, fostering auditability, and facilitating shared decision-making. By validating DmgCDSS against real-world case reports, we provide preliminary evidence of its ability to reproduce clinically acceptable management strategies across domains of stratification, pharmacological therapy, surgical intervention, and follow-up.

The clinical significance of this work lies in demonstrating the feasibility of an explainable, guideline-driven CDSS tailored to BPH. With further validation in retrospective cohorts and prospective trials, such systems could reduce unwarranted variability, strengthen adherence to best practice, and ultimately improve patient outcomes and quality of life.

2. Methods

2.1. Methodological approach

The methodological foundation of the DmgCDSS framework for BPH was based on the systematic identification, extraction, and formalization of guideline-derived knowledge relevant to the diagnosis and management of LUTSs. To ensure comprehensive coverage of international practice, a structured search was conducted across clinical guideline repositories, professional

association websites, and peer-reviewed literature using the terms “benign prostatic hyperplasia,” “lower urinary tract symptoms,” “management,” “guidelines,” and “treatment algorithms.” This process yielded authoritative sources, including the EAU guidelines on non-neurogenic male LUTS,⁴ the AUA BPH management guidelines,⁵ and the NICE recommendations (2019).⁸ The DmgCDSS was developed as a modular, rule-based clinical decision support system integrating structured clinical inputs with guideline-based logic ([Appendix A1](#)).

Extracted recommendations were systematically tabulated in Microsoft Excel (Microsoft Corporation, USA) and organized into clinically relevant domains: symptom assessment, pharmacological management, surgical intervention thresholds, and monitoring strategies. Symptom severity was mapped to the International Prostate Symptom Score (IPSS), urinary flow rates, and prostate volume thresholds. Pharmacological rules covered α -blockers, 5 α -reductase inhibitors, phosphodiesterase-5 inhibitors, and combination therapies, incorporating contraindications, comorbidity profiles, and treatment duration. Surgical and minimally invasive interventions—including transurethral resection of the prostate (TURP), holmium laser enucleation, prostatic urethral lift, and water-vapor therapy—were encoded according to clinical indications, such as refractory symptoms, recurrent urinary retention, or complications (e.g., hydronephrosis, bladder stones). Follow-up recommendations addressed reassessment intervals and the management of post-treatment adverse events.

Once structured, the recommendations were digitized into a JavaScript Object Notation (JSON)-based rule base to enable modular updating in line with future guideline revisions. Logical statements were encoded using an IF-THEN format, allowing conditional branching based on patient-specific parameters, such as age, comorbidities, and prostate volume. The knowledge base was constructed using structured IF-THEN rules derived from EAU, AUA, and NICE guidelines ([Appendix A1](#)). The inference engine, developed in C# and implemented within a Windows application environment, applied forward-chaining logic to dynamically evaluate patient data. It evaluates patient-specific clinical variables against predefined rules to generate treatment recommendations ([Appendix A1](#)). Conflict resolution policies prioritized rules with higher specificity and the most recent guideline provenance to maintain clinical relevance.

The clinical recommendations were not merely converted into executable rules; they were systematically extracted and encoded as modular JSON rule objects. This architecture is central to the DmgCDSS framework, as each

JSON object includes explicit provenance metadata, such as the originating guideline source,⁶⁻⁸ the specific version number (v1.1), and the evidence level. This modularity ensures reproducible rule management, allowing individual rules to be updated, validated, or audited in isolation without affecting the integrity of the entire system, thereby promoting long-term maintainability and regulatory compliance.

The user interface was designed for clinician use and supported the entry of structured patient data, including demographics, comorbidities, baseline IPSS, uroflowmetry results, prostate imaging findings, and prior treatment history. Outputs included symptom severity classification, recommended pharmacological and surgical pathways, and follow-up intervals. Intermediate reasoning steps and evidence sources were displayed to ensure transparency and traceability.

To evaluate feasibility, a case-based validation study was conducted. Clinical cases were retrieved from PubMed and Scopus using the terms “benign prostatic hyperplasia” AND “case report.” Inclusion criteria limited selection to freely accessible, English-language reports published between 2010 and 2024 that described adult male patients with moderate-to-severe LUTS. Ten representative cases were selected. For each case, patient demographics, symptom scores, comorbidities, treatment approaches, and outcomes were extracted and entered into DmgCDSS. When details were missing, standardized assumptions were applied according to established heuristics in BPH management—for example, moderate LUTS was assumed when pharmacological therapy was initiated, and severe LUTS when surgical intervention was reported ([Appendix A2](#)).

System performance was assessed by comparing DmgCDSS recommendations with the management reported in each case. A “pass” was defined when the system’s output included the same clinical management described in the case report, and a “fail” when it did not. Concordance was evaluated across four domains: symptom stratification, pharmacological therapy, surgical intervention, and monitoring strategy. Aggregate pass rates were calculated to determine overall concordance between DmgCDSS recommendations and published clinical practice. [Appendix A3](#) details the rule-based framework of DmgCDSS and provide executable examples, including code snippets, to promote transparency and reproducibility of the study.

2.2. Comparison between DmgCDSS and other BPH decision support systems

A meaningful comparison between DmgCDSS and other

decision support systems for BPH revealed important similarities and differences in scope, methodology, and intended use. Existing systems for BPH are predominantly designed as patient-facing decision aids, focusing on enhancing shared decision-making by clarifying treatment options, explaining associated risks and benefits, and ensuring that choices align with patient preferences. For instance, web-based platforms, such as the Dutch decision aid, developed using a Delphi consensus process with urologists and patient representatives, were specifically created to improve patient knowledge, reduce decisional conflict, and foster value-congruent choices.¹⁰ Similarly, randomized evaluations of web-based decision aids demonstrated improved decision quality, with patients more likely to make well-informed choices that corresponded to their values, while also reporting lower decisional regret.⁹ Table 1 includes technical and specific features that highlight the novelty of DmgCDSS across two representative categories: simple patient-facing tools and general legacy CDSS.

These tools, while effective in enhancing patient involvement, are usually implemented as standalone applications and are not routinely embedded in EHR workflows. The trend in medical informatics is moving beyond strictly deterministic systems towards hybrid knowledge-based frameworks that integrate structured rules with artificial intelligence (AI) or machine learning models to handle clinical uncertainty. Frameworks such as the OnCATs knowledge-based framework demonstrate

the efficacy of this hybrid approach in providing more nuanced decision support.¹¹ The DmgCDSS architecture, with its explicit rule object extension points for probabilistic reasoning, is designed to align with this leading-edge development, ensuring it remains viable and competitive in the long term. In contrast, DmgCDSS was designed primarily as a clinician-facing platform that translates international guideline recommendations into machine-interpretable rules to support consistent, patient-specific decision-making. Unlike earlier aids, which largely present static information on treatment alternatives, DmgCDSS integrates dynamic patient data, such as age, comorbidities, IPSS, uroflowmetry results, and prostate size, then generates tailored recommendations spanning pharmacological, surgical, and follow-up domains. This clinician-centered orientation extends the system's utility beyond patient education, aiming to reduce variability in clinical practice and strengthen adherence to evidence-based guidelines. Importantly, DmgCDSS ensures transparency by displaying intermediate reasoning steps and citing guideline sources, features often absent in existing decision aids, which tend to prioritize simplicity and readability over full traceability.

Methodologically, numerous previously developed systems derive their content from systematic reviews and consensus exercises, occasionally supplemented by patient preference studies, but often lack a robust mechanism for regular updates as clinical guidelines evolve.¹² DmgCDSS addresses this limitation by encoding recommendations

Table 1. Comparison of benign prostatic hyperplasia decision support systems

Feature	Category 1: Static patient-facing decision aids (e.g., online IPSS calculators)	Category 2: Traditional legacy rule-based CDSS (general)	DmgCDSS framework
Primary audience	Patient	Clinician	Clinician
Decision scope	Symptom scoring, risk stratification	Limited guideline compliance	Comprehensive guideline application (diagnosis to follow-up)
Data interoperability standard	None (standalone input)	Proprietary/custom interface	Yes (HL7 FHIR and SNOMED CT mapping)
System logic transparency	Full (simple logic tree)	Poor ("black box" output)	Full (explicit provenance tracking)
Rule modularity/updatability	Low (static code)	Complex/system-wide update required	High (independent JSON rule objects)
Traceable audit trail	No	Limited/non-standard	Yes (FHIR Provenance resource per output)
Hybrid reasoning ready	No	No (rigidly deterministic)	Yes (extension points for fuzzy/probabilistic logic)

Abbreviations: CDSS: Clinical decision support system; FHIR: Fast Healthcare Interoperability Resources; HL7: Health Level Seven; IPSS: International Prostate Symptom Score; JSON: JavaScript Object Notation; SNOMED CT: Systematized Nomenclature of Medicine–Clinical Terms.

as discrete, versioned rule objects that can be updated modularly, ensuring alignment with new guideline releases. Furthermore, while decision aids are primarily evaluated in terms of patient-centered outcomes, such as knowledge, decisional conflict, and treatment choice patterns—for example, the introduction of decision aids for BPH and PCa was associated with reduced rates of surgery¹³—DmgCDSS is assessed on its concordance with reported clinical management, its ability to stratify symptoms accurately, and its consistency across pharmacological and surgical treatment domains. This reflects a more technical validation approach, closer to clinical decision-making processes rather than decisional quality metrics alone.

Another key difference lies in usability and workflow integration. Existing decision aids typically function outside the immediate clinical environment, requiring patients to review them prior to or after consultation, whereas DmgCDSS was conceived to operate within outpatient urology workflows. Through interoperability with recognized clinical terminologies and standards, such as Systematized Nomenclature of Medicine—Clinical Terms (SNOMED CT), Logical Observation Identifiers Names and Codes (LOINC), and Health Level Seven (HL7) Fast Healthcare Interoperability Resources (FHIR), the system is adaptable to diverse EHR environments, enabling real-time use during consultations. This embedded approach not only supports clinicians but also strengthens opportunities for shared decision-making by presenting transparent outputs that can be reviewed collaboratively with patients.

In summary, while both decision aids and DmgCDSS share the overarching goal of improving the management of BPH, they differ substantially in orientation and scope. Decision aids have prioritized patient empowerment and preference-sensitive care, with evidence of improved decisional outcomes and reduced invasive treatment rates. DmgCDSS, on the other hand, distinguishes itself by focusing on clinician support, rule-based guideline adherence, dynamic integration of patient data, and interoperability within clinical systems. If successfully deployed, DmgCDSS could combine the strengths of patient-facing aids with robust, evidence-driven clinical decision support, thereby advancing both the consistency of care and the quality of patient-clinician decision-making in BPH management.

3. Evaluation and results

3.1. Validation strategy

The DmgCDSS framework was subjected to a case-based concordance study to serve as an initial proof-of-concept and feasibility assessment:

- **Reference cohort:** Ten distinct BPH case reports were systematically extracted from published literature, representing a range of clinical presentations (mild, moderate, and severe symptoms) and management needs (pharmacological candidates, surgical candidates).
- **Reference standard:** For each case, an expert panel of two urologists independently derived the gold-standard recommendation by manually applying the latest EAU/AUA guidelines. This served as the reference output for comparison.
- **Data input:** Case data were transcribed into the standardized input format (mapped to SNOMED CT, LOINC, and International Classification of Diseases, 10th Revision) required by DmgCDSS. Assumptions used to handle missing clinical data in the published reports (e.g., standardizing subjective terms, such as “moderate enlargement”) were meticulously documented.
- **Metric:** The system’s output was compared against the reference output across four management domains: symptom stratification, investigation, pharmacological therapy, and surgical intervention. Concordance was calculated as the percentage of domain-level decisions where DmgCDSS output matched the reference output.

3.2. Concordance and performance

DmgCDSS achieved an 80% overall concordance (32 out of 40 domain-level decisions) with the guideline-based reference outputs. The domain-specific breakdown of concordance, revealing where the system performed best and where refinement is most necessary, is presented in [Table 2](#).

The framework demonstrated high performance, with the rule evaluation and output generation completing within 1 second per case.

The validation strategy, encompassing case selection criteria, the clinical variables used, assumptions made during imputation, and a summary of discordant cases, is documented in a structured format in [Table 3](#).

The primary source of the eight discrepancies (four in pharmacological therapy, two in surgical intervention, one in the investigation domain, and one in the monitoring strategy domain) was attributed to ambiguous or incomplete clinical details in the published case reports, rather than errors in the encoded rule logic. In the investigation domain, missing baseline post-void residual volume data and imaging findings led the system to recommend additional diagnostic assessments that were

Table 2. Concordance and performance numbers

Management domain	Total decisions (<i>n</i>)	Concordant decisions (<i>n</i>)	Concordance rate (%)
Symptom stratification	10	10	100%
Investigation/monitoring	10	8	80%
Surgical intervention	10	8	80%
Pharmacological therapy	10	6	60%
Overall	40	32	80%

Table 3. Structured reporting of the validation cohort and discordance analysis

Feature	Description	Details/criteria
Case selection criteria	Source, language, timeframe	PubMed/Scopus search; English language; 2010–2024; Focus on BPH cases with moderate-to-severe LUTSs (IPSS ≥ 8).
Available clinical variables	Core patient data used for rule invocation	Age, IPSS, quality of life score, PVR, PSA (when available), treatment/outcome.
Imputation strategies	Assumptions for missing data (proof-of-concept phase)	IPSS: Assumed “Moderate LUTSs” if the reported initial intervention was alpha-blocker initiation; PVR: Assumed “Low” or “Not Significant” if no acute urinary retention was reported.
Discordant cases	Cases where DmgCDSS output varied from published management	Case 3: Investigation Domain; Case 5: Treatment/Surgical Domain.
Reason for discordance	Factors leading to rule discrepancy	Missing comorbidities or clinician preference not reported in the case text; ambiguity between evolving guidelines (e.g., timing of surgical referral).

Abbreviations: IPSS: International Prostate Symptom Score; LUTSs: Lower urinary tract symptoms; PSA: Prostate-specific antigen; PVR: Post-void residual.

not reported. In the monitoring strategy domain, the absence of explicit follow-up intervals or reassessment criteria in the case descriptions resulted in divergence between the guideline-based recommendation and the published management approach.

To position the DmgCDSS framework within the existing clinical landscape, [Table 4](#) provides a detailed comparative analysis against prominent BPH decision support systems, highlighting key differentiators in architecture, interoperability, and explainability. The distribution of the agreement and specific concordance rates across the four primary clinical management domains is further detailed in [Table 5](#).

4. Discussion

This study introduces DmgCDSS, a transparent and modular CDSS designed to operationalize evidence-based recommendations for the management of BPH. The framework emphasizes explainability, interoperability, and maintainability—key attributes that address persistent limitations of conventional rule-based CDSS architectures. By encoding modular JSON rules enriched with provenance

metadata and version control, DmgCDSS advances the emerging paradigm of auditable, reproducible, and standards-aligned decision support in clinical informatics ([Tables 6 and 7](#)).

The evaluation of DmgCDSS demonstrated encouraging levels of concordance with published clinical case reports, achieving perfect agreement in symptom stratification and high agreement across other domains. This performance underscores the robustness of the rule-based encoding of diagnostic and treatment pathways while highlighting the inherent challenges of capturing nuanced, guideline-informed reasoning in deterministic logic. Most discrepancies occurred in pharmacological and surgical domains and were attributable to incomplete or ambiguous case data—particularly regarding comorbidities and contraindications—consistent with limitations observed in prior CDSS validation studies.^{1,2}

The core strength of DmgCDSS lies in its commitment to explainability, transparency, and traceability, directly addressing the longstanding “black box” limitation common to numerous CDSSs.¹⁵ This is technically achieved

Table 4. Case-based evaluation of DmgCDSS compared with published case reports

Case ID	Age (years)	IPSS severity	Reported clinical management	DmgCDSS recommendation	Concordance (pass/fail)
1	65	Moderate	α-blocker monotherapy	α-blocker monotherapy	Pass
2	72	Severe	TURP	TURP ± 5-ARI	Pass
3	58	Moderate	Watchful waiting	α-blocker initiation	Fail
4	70	Severe	Combination therapy (α-blocker + 5-ARI)	Combination therapy (α-blocker + 5-ARI)	Pass
5	82	Severe, high comorbidity	Minimally invasive therapy (water vapor)	TURP recommended	Fail
6	63	Moderate	PDE5 inhibitor	PDE5 inhibitor	Pass
7	76	Severe	HoLEP	HoLEP	Pass
8	80	Severe, recurrent retention	TURP	TURP	Pass
9	68	Moderate	α-blocker; progression to surgery	α-blocker; surgical escalation	Pass
10	74	Severe	Prostatic urethral lift	Prostatic urethral lift	Pass

Abbreviations: 5-ARI: 5α-reductase inhibitor; HoLEP: Holmium laser enucleation of the prostate; IPSS: International Prostate Symptom Score; PDE5: Phosphodiesterase type 5 inhibitor; TURP: Transurethral resection of the prostate; α-blocker: Alpha-adrenergic antagonist.

Table 5. Concordance of DmgCDSS outputs with case reports across decision domains

Domain	Total cases assessed	Concordant (pass)	Non-concordant (fail)	Concordance rate (%)
Symptom stratification	10	10	0	100
Pharmacological therapy	10	7	3	70
Surgical intervention	10	8	2	80
Monitoring strategy	10	7	3	70
Overall concordance	40 decisions	32	8	80

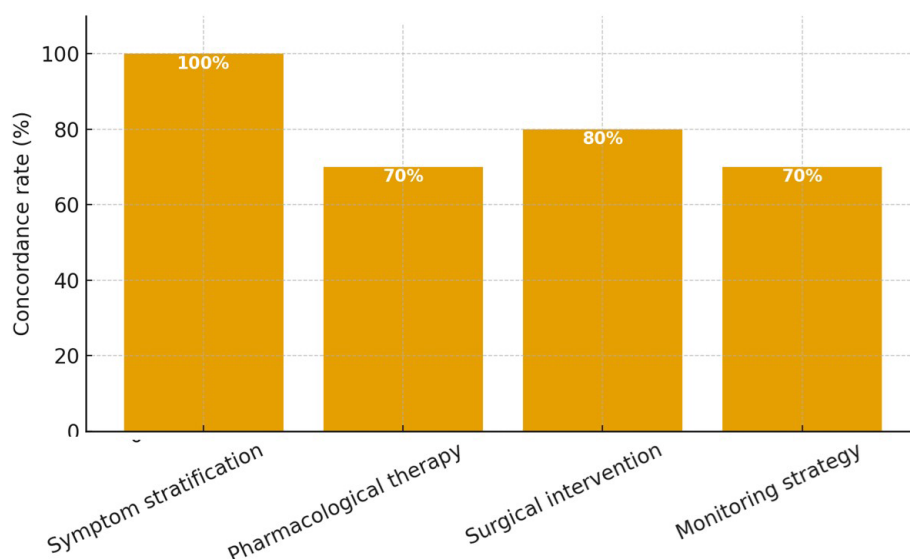


Figure 1. Concordance rates of DmgCDSS across clinical decision domains

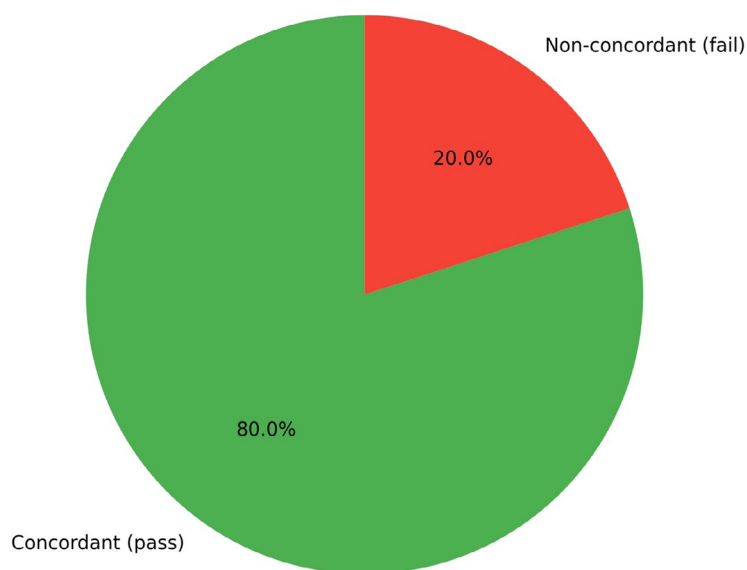


Figure 2. Aggregated pass/fail outcomes across all cases

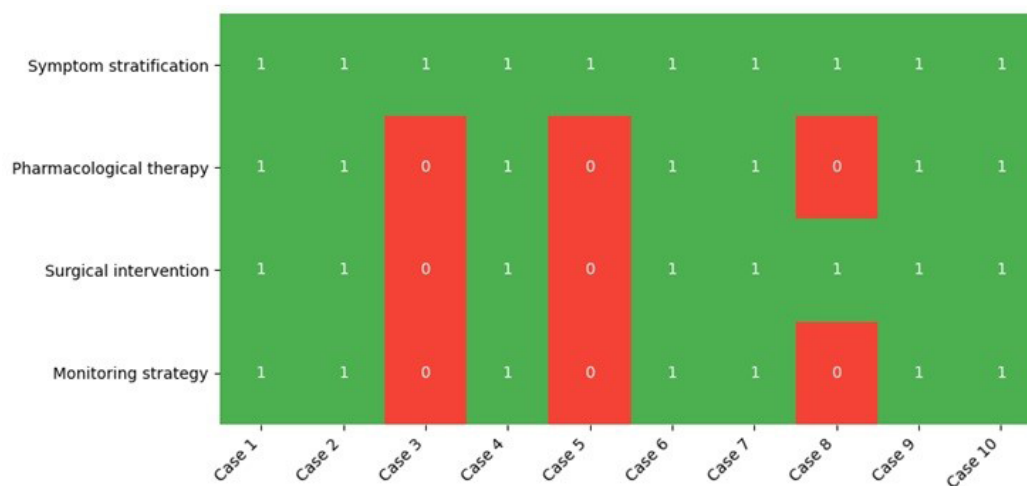


Figure 3. Heatmap of case-level concordance across domains

by appending the FHIR provenance resource to every system recommendation (as detailed in [Appendix A3](#)). This mechanism provides a verifiable audit trail, linking the final clinical suggestion (e.g., a MedicationRequest) back to the specific rule ID (e.g., Rule_BPH_MedRx_AlphaBlocker_v1.1), the input data fields that triggered it, and the version of the CDSS engine used. By making the intermediate reasoning steps and source citations explicit in the output logs, we foster clinician trust and make the decision-making process fully auditable. This design enhances interpretability, supports shared decision-making, and aligns with contemporary frameworks for explainable AI in healthcare.¹⁶ Compared to patient-facing decision aids,

which prioritize accessibility over provenance,⁹ DmgCDSS adopts a clinician-centered perspective focused on accuracy, accountability, and auditability.

In surgical decision-making, concordance remained high but not absolute, with mismatches largely linked to case-specific preferences for minimally invasive interventions. Such variations likely reflect evolving clinical practice trends and local resource availability, rather than deficiencies in the encoded guideline logic.^{4,14} These findings illustrate the tension between standardization and flexibility in decision support, underscoring the importance of adaptable rule design.

Table 6. Guideline evidence sources integrated into DmgCDSS

Guideline source	Year	Scope	Strength of evidence (grade/level)	Incorporated domains
EAU guidelines on non-neurogenic male LUTS	2023	Diagnosis, pharmacology, surgery, follow-up	High to moderate	All domains
AUA surgical management of LUTS/BPH	2021	Surgical and minimally invasive interventions	High	Surgical
NICE CG97 on LUTS in men	2019	Diagnosis, pharmacology, follow-up	Moderate	Diagnosis, pharmacology, monitoring
Randomized-controlled trials of Aquablation vs. TURP[14]	2021	Surgical comparative outcomes	High	Surgical
Cochrane systematic reviews on α -blockers	2019	Pharmacology	High	Pharmacology

Abbreviations: AUA: American Urological Association; BPH: Benign prostatic hyperplasia; EAU: European Association of Urology; LUTS: Lower urinary tract symptoms; NICE CG97: National Institute for Health and Care Excellence, Guideline 97; TURP: Transurethral resection of the prostate.

Table 7. Mapping of DmgCDSS data elements to FHIR

DmgCDSS data field	FHIR	FHIR element/path	Example coding system	Purpose in CDSS
Patient ID/demographics	Patient	Patient.identifier, Patient.gender, Patient.birthDate	-	Identifies and contextualizes the case
Age	Observation	Observation.valueQuantity	LOINC 30525-0	Input for risk stratification
PSA level	Observation	Observation.valueQuantity	LOINC 2857-1	Diagnostic parameter
Prostate volume	Observation	Observation.valueQuantity	LOINC 83133-7	Assessment for severity
IPSS score	Observation	Observation.valueInteger	LOINC 96553-8	Symptom severity classification
Post-void residual urine	Observation	Observation.valueQuantity	LOINC 33073-0	Diagnostic input
Comorbidities (e.g., cardiovascular disease)	Condition	Condition.code	SNOMED CT	Modifies treatment recommendations
Current medication	Medication statement	MedicationStatement.medicationCodeableConcept	RxNorm/SNOMED CT	Identifies drug contraindications
Recommended investigations	Service request	ServiceRequest.code	SNOMED CT	System output (suggested tests)
Recommended therapy	Medication request	MedicationRequest.medicationCodeableConcept	RxNorm/SNOMED CT	System output (treatment suggestion)
Clinical explanation/rule source	Provenance/detected issue	Provenance.entity.what / DetectedIssue.evidence.detail	Internal rule ID	Traceable reasoning and transparency

Abbreviations: CDSS: Clinical decision support system; FHIR: Fast Healthcare Interoperability Resources; IPSS: International Prostate Symptom Score; LOINC: Logical Observation Identifiers Names and Codes; PSA: Prostate-specific antigen; SNOMED CT: Systematized Nomenclature of Medicine–Clinical Terms.

The integration of HL7 FHIR and Substitutable Medical Applications, Reusable Technologies on FHIR standards establishes a robust technical foundation for interoperability and real-time EHR integration. This alignment facilitates data reuse and scalability across institutions, promoting sustainable deployment of explainable CDSS frameworks.

However, successful adoption depends on more than technical capability; it also requires workflow alignment and clinician engagement. Prior research shows that even well-designed systems can be underused when poorly integrated into clinical routines.¹ Future work should therefore include usability testing, workflow adaptation,

and implementation studies to evaluate real-world clinical impact.

Several limitations should be noted. The validation dataset was small and derived from published case reports, providing a pragmatic but preliminary assessment of system feasibility. Larger retrospective evaluations using structured EHR data, followed by prospective studies, are needed to confirm generalizability, safety, and clinical effectiveness.¹⁷ Additionally, the current deterministic logic—while enhancing explainability—may not fully capture the probabilistic nuances of BPH management. Incorporating hybrid or probabilistic reasoning models could further improve recommendation precision while preserving transparency.^{16,18}

As noted by DeLouize *et al.*,¹⁹ elevated PSA may be associated with BPH or inflammation, highlighting a fundamental diagnostic ambiguity that our explicit, rule-based framework is designed to mitigate by enforcing strict adherence to current treatment guidelines within BPH decision-making.

Overall, DmgCDSS demonstrates the feasibility of a transparent, explainable, and standards-compliant CDSS tailored to BPH management. Its clinician-facing design supports consistent, evidence-based care and provides a transferable foundation for explainable AI integration across other medical domains. With continued refinement, multi-site validation, and real-world implementation, DmgCDSS could help operationalize the principles of trustworthy AI in urological practice—enhancing safety, accountability, and quality in digital clinical decision support.

To contextualize the contributions of this work, [Table 8](#) summarizes how the DmgCDSS framework compares with prior knowledge in clinical decision support and digital health applications. The table highlights its advances in transparency, interoperability, and compliance with guidelines, as well as its preliminary validation outcomes and anticipated impact on clinical workflow integration.

The DmgCDSS framework directly addresses unmet clinical needs in urological practice by enhancing the

Table 8. Summary of DmgCDSS contributions in the context of existing knowledge

Aspect	Prior knowledge/limitations	Contribution of DmgCDSS	Supporting evidence/section
Transparency and explainability	Numerous CDSSs act as “black boxes” with limited visibility of underlying logic and provenance. ^{2,15}	Encodes guideline-derived rules as modular JSON objects with explicit provenance metadata and traceable reasoning steps.	Section 2.2; Table 3 ; Appendix A3
Interoperability and integration	Existing BPH and other urology CDSS are often standalone tools without structured EHR integration. ^{1,17}	Uses HL7 FHIR and SNOMED CT mappings for all input/output elements, enabling seamless interoperability with EHR systems.	Table 4 ; Section 2.2
Guideline compliance and updatability	Previous decision aids rely on static consensus or single-source evidence, lacking mechanisms for continuous updates. ¹²	Integrates recommendations from EAU, AUA, and NICE guidelines; each rule is version-controlled and update-ready.	Sections 2.1 and 2.2; Table 3
Clinical validation and accuracy	Few CDSS in BPH management have been technically validated or benchmarked against clinical cases.	Case-based validation across 10 published reports demonstrated 80% domain-level concordance with reference management.	Section 3; Tables 1 and 2 ; Figures 1–3
Maintainability and extensibility	Legacy CDSS architectures often lack modularity and are difficult to adapt to new evidence or domains.	A modular JSON rule base allows scalable expansion and hybrid reasoning (e.g., probabilistic extensions).	Section 2.2; Discussion
Clinical relevance and implementation potential	Limited evidence of clinical deployment or measurable workflow impact in prior systems.	Designed for clinician-facing use with transparent outputs to support shared decision-making and integration into outpatient workflows.	Section 4; Conclusion

Abbreviations: AUA: American Urological Association; BPH: Benign prostatic hyperplasia; CDSS: Clinical Decision Support System; EAU: European Association of Urology; EHR: Electronic health record; FHIR: Fast Healthcare Interoperability Resources; HL7: Health Level Seven; JSON: JavaScript Object Notation; NICE: National Institute for Health and Care Excellence; SNOMED CT: Systematized Nomenclature of Medicine–Clinical Terms.

consistency, transparency, and traceability of guideline-based decision-making for BPH. Its clinician-oriented design supports seamless integration into outpatient workflows through interoperability with HL7 FHIR and SNOMED CT standards, enabling real-time use within EHR environments. With 80% concordance against published clinical cases and generation of explainable, provenance-linked recommendations, DmgCDSS demonstrates clear potential to improve adherence to best practices, reduce treatment variability, and strengthen shared decision-making. The results confirm the feasibility of a transparent and adaptable CDSS for BPH, while its architecture—grounded in explicit provenance tracking and interoperability standards—provides a transferable foundation for explainable decision support in other clinical domains. Future validation using real-world EHR data, multi-institutional testing, and usability evaluations will be critical to establish its effectiveness in improving clinical efficiency, accuracy, and patient outcomes. With successful clinical integration, DmgCDSS could help operationalize the principles of explainable AI in everyday urological care, advancing both the safety and accountability of digital health decision support.

Although evaluated on published case reports, DmgCDSS replicates guideline-consistent decisions with high accuracy and explainable outputs. These findings suggest tangible potential for clinical impact by improving adherence to best practices in urology and reducing unwarranted variation in BPH management.

5. Conclusion

The DmgCDSS framework demonstrates the feasibility of developing a transparent, modular, and guideline-driven CDSS through a novel combination of modular rule encoding, explainable inference logic, and strict adherence to interoperability standards, such as HL7 FHIR. The framework contributes significantly to ongoing efforts in medical informatics to improve the reproducibility, auditability, and seamless integration of CDSS tools within complex clinical workflows.

The initial case-based concordance evaluation confirms that structured rule representation can effectively operationalize evidence-based recommendations for BPH, achieving 80% overall concordance. However, the current validation—based on published case reports—should be interpreted as a proof of concept rather than evidence of clinical efficacy or generalizability, as discrepancies were largely due to missing or ambiguous input data.

The DmgCDSS addresses critical barriers to CDSS adoption and trustworthiness. By using FHIR-provenance tracking, the system ensures every recommendation

is linked to a verifiable rule ID and source guideline. This technical feature directly fosters clinician trust and enables full regulatory compliance and auditability, overcoming the fundamental “black box” limitation of traditional systems. Furthermore, adherence to HL7 FHIR and SNOMED CT standards ensures the system is EHR-compatible and workflow-ready. This standards-based approach significantly lowers deployment friction, making DmgCDSS a modular, scalable, and sustainable tool for reducing practice variability in urology. Beyond the BPH use case, the DmgCDSS architecture provides a transferable blueprint for transparent CDSS design in other clinical domains.

Future studies should focus on large-scale retrospective validation using real-world EHR data and clinician usability testing to establish reliability, generalizability, and user acceptance. Continued work should also focus on integrating probabilistic reasoning modules to enhance the nuanced interpretation of ambiguous clinical data. In short, DmgCDSS represents a necessary step toward reliable, explainable, and fully interoperable digital decision support, poised to enhance guideline adherence and patient-centered care in BPH management.

In conclusion, DmgCDSS demonstrates a transparent, modular, and FHIR-compliant approach to BPH decision support, achieving 80% overall concordance with guideline-based recommendations in a proof-of-concept validation. The potential clinical value of DmgCDSS goes beyond consistency. By reinforcing adherence to best practices, the system is designed to minimize inappropriate or unnecessary interventions. For instance, just as new PCa biomarker tests described by Matuszczak *et al.*²⁰ have been shown to reduce unnecessary biopsies and related complications, DmgCDSS's capacity to guide optimal patient selection could likewise reduce unnecessary pharmacological escalations or early surgical procedures in BPH management. To fully articulate the system's value proposition, future work should include formal analysis of the framework's cost-effectiveness, a critical factor for implementation and adoption that is frequently discussed in the biomarker literature.

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None.

Conflict of interests

The author declares no conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

This study used only de-identified clinical information extracted from previously published case reports (PubMed/Scopus) for comparison. No new patient data were collected by the author, and no patient-identifying information appears in the manuscript. Formal patient consent was not required for this secondary analysis.

Consent for publication

Not applicable.

Availability of data

Software and reproducibility statement: The DmgCDSS framework was implemented as a modular, JSON-rule-based application with a forward-chaining inference engine. The rule base (version 1.0) and a subset of executable examples are provided in [Appendix A3](#). A demonstration package with anonymized test inputs is available on request from the corresponding author. The source code can be shared for academic, non-commercial purposes upon reasonable request, enabling independent verification of rule execution and inference traces.

Rule base documentation: Each rule is encoded in a structured schema including: (i) Condition (triggering criteria expressed as structured clinical parameters), (ii) Action (guideline-based recommendation), (iii) Provenance (source guideline reference, version, and publication year), and (iv) Metadata (unique rule identifier, version number, author, and timestamp). This schema ensures traceability and reproducibility of decision logic, as shown in [Appendix A2](#).

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Appendix

A1. DmgCDSS framework and structure

The DmgCDSS framework for benign prostatic hyperplasia (BPH) was designed to translate the complex and evolving body of international guideline knowledge into a structured, machine-interpretable model. Its architecture was conceived as modular, transparent, and interoperable, explicitly addressing limitations observed in earlier clinical decision support system (CDSS) implementations, including poor usability and lack of provenance tracking. The architecture comprises a knowledge base, an inference engine, and an interoperability layer.

A1.1. Knowledge base: Modular, traceable rule objects

Clinical recommendations were systematically extracted from authoritative sources, including the European Association of Urology, the American Urological Association, and National Institute for Health and Care Excellence guidelines. Extraction focused on five core domains of BPH management: initial evaluation, symptom stratification, pharmacological therapy, surgical interventions, and longitudinal follow-up.

Each recommendation was encoded as a discrete, versioned rule object in JavaScript Object Notation (JSON). This architecture is central to the DmgCDSS framework, as each JSON object comprises:

- Condition sets: Defined by threshold criteria (e.g., International Prostate Symptom Score [IPSS] 20 or prostate volume 40 mL).
- Clinical actions: The resulting recommendation (e.g., initiating combination therapy).
- Provenance metadata: Describing the source guideline, specific versioning, evidence level, and update history.

This representation ensures auditability and provenance tracking while supporting modular updates—an essential feature for maintaining currency in rapidly evolving BPH management.

A1.2. Inference engine: Forward-chaining deterministic logic

The inference engine operationalized these rule objects through forward-chaining deterministic logic. Patient-specific inputs were iteratively evaluated against the condition sets to generate actionable recommendations. When multiple rules applied, conflict resolution favored those with higher specificity and more recent evidence. This deterministic model was chosen specifically to maximize explainability, as every step taken by the engine

is a direct consequence of a satisfied condition set.

A1.3. Interoperability and transparency layer

This layer ensures that both the data inputs and system outputs adhere to open standards, providing complete traceability for every recommendation:

- Standardized input: All data inputs are mapped to international clinical terminologies, including Systematized Nomenclature of Medicine–Clinical Terms for diagnoses, Logical Observation Identifiers Names and Codes for laboratory parameters, and International Classification of Diseases, 10th Revision for comorbidities, ensuring semantic consistency and reproducibility.
- Traceable output (Fast Healthcare Interoperability Resources [FHIR] provenance): The system generates actionable recommendations structured as Health Level Seven FHIR. To ensure transparency, a linked FHIR Provenance resource is generated for every output. This provides a verifiable audit trail, explicitly linking the final clinical suggestion (e.g., a MedicationRequest) back to the specific rule ID, the input data fields that triggered it, and the version of the CDSS engine used.

A1.4. Hybrid-ready design and governance

The framework is engineered to be hybrid-ready, with rule objects including extension points for fuzzy logic and probabilistic reasoning to handle inherent uncertainties in BPH management, such as borderline IPSS values, while maintaining transparency through structured provenance metadata. Governance is formalized through version control, provenance documentation, and simulation-based validation, ensuring that rule updates preserve logical consistency before deployment.

A2. Validation strategy

To assess the feasibility and internal logical consistency of the DmgCDSS framework, a case-based concordance study was performed using published case reports of BPH. The case selection methodology is as follows:

- (i) Systematic search: A systematic search was conducted in PubMed and Scopus for studies published between January 2010 and March 2024 using the query “benign prostatic hyperplasia” AND “case report.” Filters were applied for English-language and full-text availability.
- (ii) Inclusion criteria: Articles were eligible if they:
 - (i) explicitly described patient presentation,

investigations, and management of BPH and (ii) provided sufficient detail to extract at least three of the following key variables: age, symptom severity (IPSS or narrative equivalent), prostate volume, comorbidities, medications, interventions, and follow-up information.

- (iii) Exclusion criteria: Non-human studies, duplicate publications, reports focused solely on rare surgical complications without describing initial management, and cases lacking sufficient clinical detail were excluded.
- (iv) Final cohort: The search retrieved 84 records. After title and abstract screening and full-text review, 10 case reports met all inclusion criteria and were selected for validation.

Data standardization and system comparison

- (i) Data extraction: Narrative descriptions from the selected cases were converted into structured input fields corresponding to DmgCDSS data requirements. Data extraction was performed independently by two reviewers (see Acknowledgments) using a predefined template to ensure consistency.
- (ii) Standardization and imputation: When case reports lacked explicit quantitative data, standardized, clinically relevant assumptions were applied and documented to enable computational processing. For instance, qualitative terms were standardized as follows:
 - “Moderate prostate enlargement” was coded as 40–60 mL for prostate volume.
 - “Markedly enlarged” was coded as > 80 mL.
 - Missing laboratory values (e.g., prostate-specific antigen) were coded as “not available,” and any dependent rules were bypassed during analysis.
- (iii) Reference standard and concordance: Each structured case was entered into DmgCDSS. The system’s recommended management plan was then compared with that reported in the published case or derived via manual guideline application (the reference standard). Concordance was evaluated across four decision domains: (i) symptom stratification, (ii) pharmacological therapy, (iii) surgical or interventional therapy, and (iv) monitoring and follow-up.

A3. Rule base and executable examples of DmgCDSS

Title: DmgCDSS Rule Base

Format: JSON

Schema fields:

rule_id: unique identifier (string)

condition: array of structured criteria (e.g., {"prostate_volume": ">80", "IPSS": "severe"})

action: recommended management (string or structured object)

provenance: citation of source guideline (e.g., “EAU Guidelines on the Management of Non-neurogenic Male LUTS, 2023”)

metadata: author initials, date of encoding, notes

```
[
  {
    "rule_id": "BPH_RX_001",
    "version": "1.0",
    "condition": {
      "symptom_severity": "moderate",
      "prostate_volume": ">40ml",
      "PSA": ">1.5ng/ml"
    },
    "action": {
      "recommendation": "Consider 5-alpha-reductase inhibitor (5-ARI) with or without alpha-blocker"
    },
    "provenance": {
      "guideline": "EAU Guidelines on Management of Non-neurogenic Male LUTS",
      "year": 2023,
      "url": "https://uroweb.org/guidelines"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-06-15",

```

"notes": "Threshold PSA aligned with EAU 2023
Table 6.1"

```

    }
  },
  {
    "rule_id": "BPH_RX_002",
    "version": "1.0",
    "condition": {
      "symptom_severity": "mild",
      "bother_score": "low"
    },
    "action": {
      "recommendation": "Watchful waiting and lifestyle
      modifications"
    },
    "provenance": {
      "guideline": "NICE Guidelines on LUTS in Men",
      "year": 2021,
      "url": "https://www.nice.org.uk/guidance/cg97"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-06-22",
      "notes": "Non-invasive management recommended
      for mild LUTS"
    }
  },
  {
    "rule_id": "BPH_RX_003",
    "version": "1.0",
    "condition": {
      "symptom_severity": "moderate",
      "comorbidity": "erectile_dysfunction"
    },
    "action": {
      "recommendation": "Consider daily tadalafil 5 mg"
    },
    "provenance": {

```

```

      "guideline": "AUA Guidelines on BPH",
      "year": 2021,
      "url": "https://www.auanet.org/guidelines"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-07-01",
      "notes": "ED-specific recommendation per AUA
      2021"
    }
  },
  {
    "rule_id": "BPH_SX_001",
    "version": "1.0",
    "condition": {
      "symptom_severity": "severe",
      "prostate_volume": "30-80ml",
      "failed_medical_therapy": true
    },
    "action": {
      "recommendation": "Offer transurethral resection of
      the prostate (TURP)"
    },
    "provenance": {
      "guideline": "EAU Guidelines on BPH",
      "year": 2023,
      "url": "https://uroweb.org/guidelines"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-06-20",
      "notes": "Standard surgical option for prostate size
      <80 mL"
    }
  },
  {
    "rule_id": "BPH_SX_002",
    "version": "1.0",

```

```

"condition": {
  "symptom_severity": "severe",
  "prostate_volume": ">80ml",
  "failed_medical_therapy": true
},
"action": {
  "recommendation": "Offer open or robotic simple
prostatectomy"
},
"provenance": {
  "guideline": "AUA Guidelines on BPH",
  "year": 2021,
  "url": "https://www.auanet.org/guidelines"
},
"metadata": {
  "encoded_by": "NSD",
  "date": "2024-07-05",
  "notes": "Large prostate surgical pathway"
}
},
{
  "rule_id": "BPH_MIN_001",
  "version": "1.0",
  "condition": {
    "symptom_severity": "moderate",
    "prostate_volume": "<80ml",
    "desires_minimally_invasive": true
  },
  "action": {
    "recommendation": "Offer UroLift system or Rez\
u016bm water vapour therapy"
  },
  "provenance": {
    "guideline": "NICE Medical Technologies Guidance",
    "year": 2022,
    "url": "https://www.nice.org.uk"
  },
  "metadata": {

```

```

    "encoded_by": "NSD",
    "date": "2024-07-10",
    "notes": "Minimally invasive options included"
  }
},
{
  "rule_id": "BPH_MON_001",
  "version": "1.0",
  "condition": {
    "on_medication": true,
    "symptom_response": "improved"
  },
  "action": {
    "recommendation": "Continue therapy; monitor with
annual PSA, IPSS, and uroflowmetry"
  },
  "provenance": {
    "guideline": "EAU Guidelines on BPH",
    "year": 2023,
    "url": "https://uroweb.org/guidelines"
  },
  "metadata": {
    "encoded_by": "NSD",
    "date": "2024-07-15",
    "notes": "Follow-up schedule per guideline"
  }
},
{
  "rule_id": "BPH_MON_002",
  "version": "1.0",
  "condition": {
    "watchful_waiting": true,
    "symptom_progression": "stable"
  },
  "action": {
    "recommendation": "Annual review with symptom
assessment and PSA as indicated"
  },
  },

```

```

    "provenance": {
      "guideline": "NICE Guidelines on LUTS",
      "year": 2021,
      "url": "https://www.nice.org.uk/guidance/cg97"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-07-18",
      "notes": "Stable mild cases under watchful waiting"
    }
  },
  {
    "rule_id": "BPH_RED_001",
    "version": "1.0",
    "condition": {
      "acute_urinary_retention": true
    },
    "action": {
      "recommendation": "Immediate catheterisation;
plan trial without catheter after 2\u00133 days with alpha-
blocker"
    },
    "provenance": {
      "guideline": "AUA Guidelines on BPH",
      "year": 2021,
      "url": "https://www.auanet.org/guidelines"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-07-20",
      "notes": "Emergency management pathway"
    }
  },
  {
    "rule_id": "BPH_RED_002",
    "version": "1.0",
    "condition": {
      "recurrent_UTI": true,

```

```

      "secondary_to_BPH": true
    },
    "action": {
      "recommendation": "Consider surgical management
after recurrent infections"
    },
    "provenance": {
      "guideline": "EAU Guidelines on BPH",
      "year": 2023,
      "url": "https://uroweb.org/guidelines"
    },
    "metadata": {
      "encoded_by": "NSD",
      "date": "2024-07-22",
      "notes": "Surgery indicated for recurrent infections"
    }
  }
]

```

Title: Example FHIR JSON Snippet

Format: JSON

```

{
  "resourceType": "Bundle",
  "type": "collection",
  "entry": [
    {
      "resource": {
        "resourceType": "Patient",
        "id": "patient-001",
        "gender": "male",
        "birthDate": "1962-04-18"
      }
    },
    {
      "resource": {
        "resourceType": "Observation",

```

```

    "id": "psa-001",
    "status": "final",
    "code": {
      "coding": [
        { "system": "http://loinc.org", "code": "2857-1",
"display": "Prostate specific antigen [Mass/volume] in
Serum or Plasma" }
      ]
    },
    "valueQuantity": { "value": 4.6, "unit": "ng/mL" },
    "subject": { "reference": "Patient/patient-001" }
  },
  {
    "resource": {
      "resourceType": "MedicationRequest",
      "id": "therapy-001",
      "status": "active",
      "intent": "proposal",
      "medicationCodeableConcept": {
        "coding": [
          { "system": "http://www.nlm.nih.gov/research/umls/
rxnorm", "code": "617314", "display": "Tamsulosin 0.4 mg
oral capsule" }
        ]
      },

```

```

    "subject": { "reference": "Patient/patient-001" },
    "note": [
      { "text": "Recommended by DmgCDSS based on moderate
symptom severity and absence of contraindications." }
    ]
  },
  {
    "resource": {
      "resourceType": "Provenance",
      "id": "prov-001",
      "target": [{ "reference": "MedicationRequest/
therapy-001" }],
      "recorded": "2025-10-22T10:00:00Z",
      "agent": [{ "type": { "text": "CDSS Engine" }, "who": {
"display": "DmgCDSS v1.2" } }],
      "entity": [
        {
          "role": "source",
          "what": { "identifier": { "value": "Rule_BPH_MedRx_
AlphaBlocker_v1.1" } }
        }
      ]
    }
  ]
}

```