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Do Traditional Imaging Predictors Still Matter? A Systematic Review on Laser Efficiency and Stone-Free Outcomes in the Era of Advanced Lithotripsy

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Abstract: Endoscopic laser lithotripsy has become the standard treatment for urinary stones, yet preoperative imaging parameters that predict laser efficiency and stone-free outcomes remain incompletely characterized. This systematic review synthesizes evidence on current imaging-based predictors of laser efficiency and stone-free outcomes in endoscopic laser lithotripsy, with the goal of informing precision surgical planning and future predictive modeling. A systematic review was conducted following PRISMA guidelines. We screened studies evaluating adult patients (≥18 years) with urinary stones undergoing endoscopic laser lithotripsy with preoperative imaging assessment and reported relationships between imaging parameters and treatment outcomes. Data extraction included patient characteristics, imaging parameters, laser technology, efficiency metrics, stone-free outcomes, and statistical relationships. One hundred ten studies comprising 23,847 patients met inclusion criteria. Stone density >1000 HU predicted significantly lower single-session stone-free rates (40% vs 95%, $p=0.01$) and longer operative time (75±15 vs 55±13 minutes, $p<0.01$) for stones >2 cm. Stone size >20 mm reduced stone-free rates to 68% versus 100% for stones ≤20 mm, with first-procedure success of only 25.0% for bilateral total diameter >30 mm. Lower pole location independently predicted reduced stone-free rates (OR 0.523, $p<0.001$), while stone relocation improved 3-month stone-free rates from 84.4% to 97.8% ($p=0.026$). Higher BMI unexpectedly predicted improved stone-free rates (OR 1.17, $p=0.022$). Thulium fiber laser demonstrated shorter lasing time (7.4±1.8 vs 14.8±1.5 minutes, $p=0.011$) and comparable stone-free rates to Ho: YAG. The SMASH score (HU × size/100) with cut-off of 15 distinguished RIRS success rates (82% vs 61%, p=0.03). Flexible and navigable suction ureteral access sheath (FANS) achieved 94.7-97.5% stone-free rates. Stone imaging characteristics helped predict complex surgical procedures and outcomes of endoscopic lithotripsy. Imaging methods differed in their ability to predict procedural difficulty, with density being most predictive for large stones. The anatomical location and stone burden helped predict procedural feasibility and stone clearance. Support is provided for transitioning from descriptive imaging to predictive imaging-based surgical planning and the potential for imaging biomarkers and technology-dependent parameters to individualize surgery and optimize laser parameters. Stone density >1000 HU, size >20 mm, and lower pole location are validated predictors of reduced laser efficiency and stone-free outcomes. Composite scores such as Stone Management According to Size-Hardness (SMASH) score, show that radiological factors can be integrated into clinical decision-making for kidney stone management. These results will allow for the next steps towards the use of artificial intelligence–driven predictive models for personalized endoscopic stone surgery and urinary stone treatment planning.

Keywords: urinary stones, laser lithotripsy, hounsfield units, stone-free rate, predictive modeling

INTRODUCTION

Urolithiasis affects approximately 10-15% of the global population, with rising incidence worldwide (El Hamed et al., 2017; Gauhar et al., 2025). Endoscopic laser lithotripsy has revolutionized the management of urinary stones, offering minimally invasive treatment with high success rates (Xu et al., 2023; Gupta et al., 2025). The evolution of laser technologies—from low-power holmium:YAG (Ho:YAG) to high-power Ho:YAG, Moses technology, and thulium fiber laser (TFL)—has expanded treatment options while introducing complexity in device selection and surgical technique (Kozubaev et al., 2025; Chandramohan et al., 2023; A. Martov et al., 2020).

Despite technological advances, significant variability exists in treatment outcomes. Stone-free rates range from 40% to 100% depending on patient selection, stone characteristics, and surgical approach (El Hamed et al., 2017; Æsøy et al., 2025; Abushnaf et al., 2023). Preoperative imaging, particularly non-contrast computed tomography (CT), provides detailed characterization of stone parameters including density (Hounsfield units, HU), size, volume, and anatomical location (Luis Rico et al., 2024; Aksoy et al., 2022; A. I. Tursunov et al., 2022). These imaging-derived metrics potentially offer predictive value for procedural efficiency and success, enabling personalized surgical planning (Perri et al., 2023; Perri et al., 2024).

Although numerous studies have investigated individual imaging parameters as predictors of lithotripsy outcomes, the evidence remains fragmented. Key gaps include: (1) inconsistent findings regarding the predictive value of stone density across different stone sizes and locations (El Hamed et al., 2017; Haitao Liu et al., 2024; Albert et al., 2022); (2) lack of standardized definitions for laser efficiency metrics and stone-free outcomes (Gauhar et al., 2025; Gauhar et al., 2024); (3) absence of validated integrated predictive models combining multiple imaging parameters (Perri et al., 2023; Perri et al., 2024); (4) limited understanding of how technology choices (laser type, power settings, access sheaths) interact with imaging-based predictors (Chai et al., 2024; Gauhar et al., 2024); and (5) no systematic synthesis of evidence to guide AI model development for outcome prediction.

This systematic review provides the first comprehensive synthesis of imaging-based predictors specifically for endoscopic laser lithotripsy outcomes. We integrate evidence across 110 studies examining relationships between preoperative imaging parameters and both laser efficiency metrics (lasing time, energy consumption, ablation speed) and clinical outcomes (stone-free rates, secondary procedures). The review identifies validated predictors versus promising indicators requiring further study, characterizes technology-predictor interactions, and establishes evidence gaps for machine learning applications.

We hypothesize that: (1) stone density measured in Hounsfield units predicts laser efficiency and stone-free rates, with threshold effects above 1000 HU; (2) stone size and volume demonstrate non-linear relationships with outcomes, with critical thresholds at 15-20 mm; (3) lower pole location independently predicts reduced stone-free rates; (4) integrated models combining multiple imaging parameters provide superior predictive accuracy to individual parameters; and (5) advanced laser technologies (TFL, Moses) and suction sheaths (FANS) attenuate the negative predictive effects of unfavorable stone characteristics.

This synthesis will benefit clinical practice by enabling evidence-based preoperative counseling, optimizing patient selection for specific technologies, guiding surgical technique selection based on imaging characteristics, and identifying patients requiring staged procedures. For researchers, it establishes priorities for prospective validation studies and provides a framework for AI model development incorporating standardized imaging parameters and outcomes.

METHOD

Protocol

The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines to ensure methodological rigor and accuracy. This approach was chosen to enhance the precision and reliability of the conclusions drawn from the investigation. This systematic review was registered on PROSPERO (Registration Number: CRD420261396818). Risk of bias was assessed using the JBI (Joanna Briggs Institute) Critical Appraisal Tools.

Criteria for Eligibility

Population included were adult patients (≥18 years) diagnosed with urolithiasis undergoing endoscopic laser lithotripsy, including ureteroscopy (URS), retrograde intrarenal surgery (RIRS), or percutaneous nephrolithotomy (PCNL). The exposure/ intervention was preoperative imaging parameters derived from computed tomography or other imaging modalities, including hounsfield unit measurements**,** stone size and volume**,** stone location**,** skin-to-stone distance**,** dual-energy CT characteristics and radiomics or texture features.

Studies were included if they reported at least one primary outcome from the following: laser efficiency indicators (operative time, lasing time, energy usage, fragmentation performance) and/or stone-free rate (SFR). Secondary outcomes included in this study involved the retreatment rate**,** residual fragments**,** and postoperative complications.

Eligible designs included randomized trials, cross-sectional, prospective cohorts, and retrospective observational studies. Case reports, editorials, animal studies, pediatric populations, and studies involving non-laser lithotripsy were excluded.

Search Strategy

A comprehensive literature search was performed in the following databases such as PubMed, Springer, Semantic Scholar, Wiley Online Library, and Google Scholar were searched for all relevant publications from January 1, 2015, to February 2026. The Boolean MeSH keywords inputted on databases for this research are: *("Adult Patients" OR "Urinary Stones" OR "Upper Tract Stones" OR "Nephrolithiasis") AND ("Endoscopic Laser Lithotripsy" OR "Ureteroscopic Laser Stone Fragmentation" OR "Imaging Predictors" OR "Predictive Modeling") AND ("Different Imaging Parameters" OR "Various Laser Technologies" OR "Surgical Techniques" OR "Outcome Thresholds") AND ("Laser Efficiency" OR "Stone-Free Rate (SFR)" OR "Treatment Outcomes" OR "Post-Operative Success"*. Reference lists of included studies and relevant reviews were manually screened to identify additional eligible studies.

Study Selection, Data Extraction, and Synthesis

All retrieved records were imported into reference management software and duplicates were removed. Two independent reviews performed first and second screening. Abstracts of screened studies will be included in the research by contacting the authors to request the full paper. If the paper meets the criteria, it will be included in the further analysis. Disagreements were resolved through consensus discussion with a third reviewer.

Data were extracted independently by two reviewers using a standardized extraction form. When multiple imaging predictors were reported, all relevant variables were recorded. Due to substantial heterogeneity in imaging definitions, laser technologies, and outcome reporting, quantitative meta-analysis was not performed. Instead, a structured narrative synthesis was conducted. Evidence mapping framework was developed to summarize clinical relevance and future research directions.

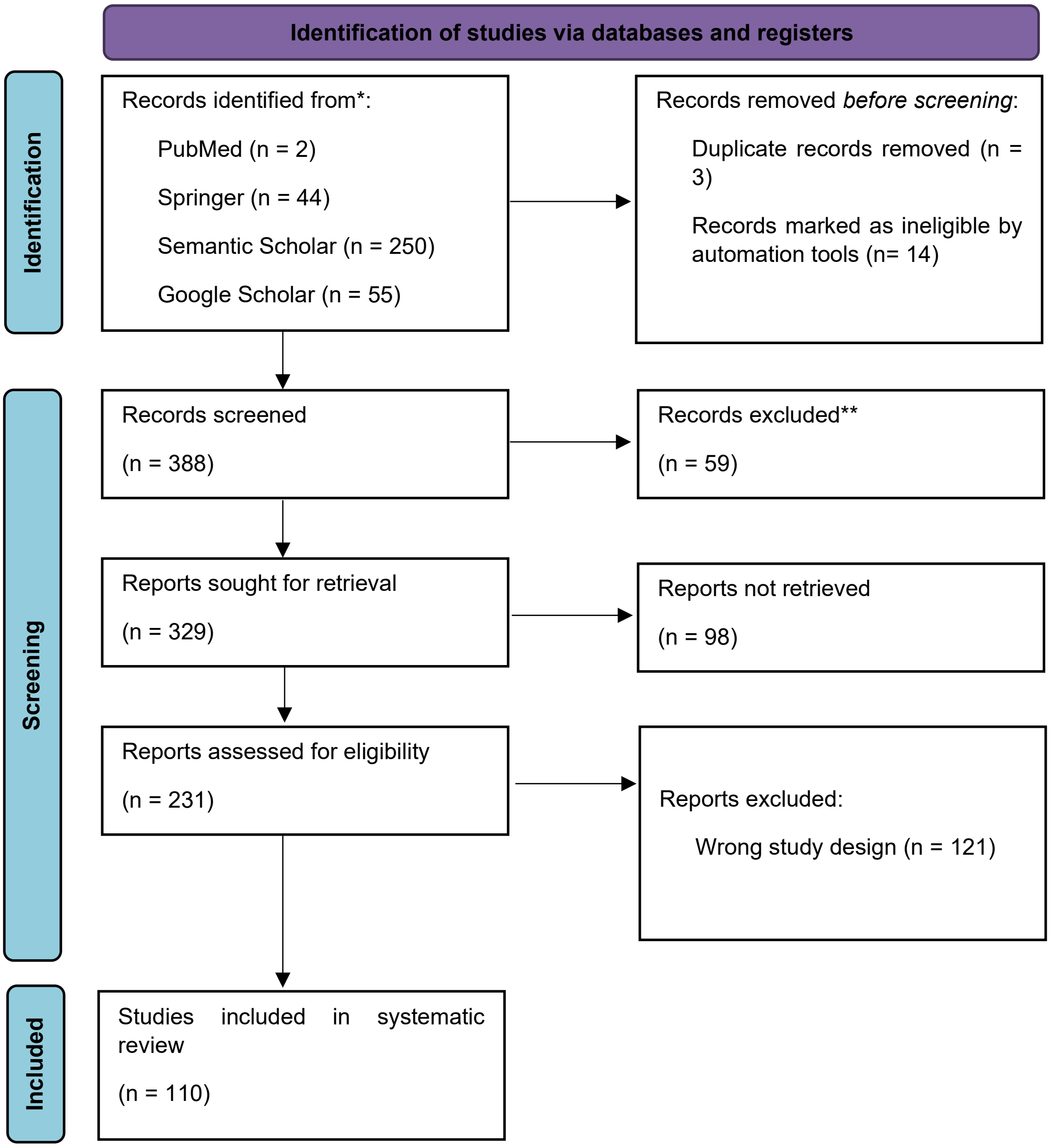

Figure 1. Article search flowchart by Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) for study selection

RESULTS AND DISCUSSION

Characteristics of Included Studies

The systematic review included 110 studies evaluating imaging-based predictors of laser efficiency and stone-free outcomes in endoscopic laser lithotripsy. Studies varied in design, sample size, and available full-text access. The included studies represented diverse clinical scenarios with stone sizes ranging from 4 mm to 5 cm and locations spanning the entire upper urinary tract. The majority were prospective studies (Gauhar et al., 2025; Meller et al., 2025; Gauhar et al., 2024; Xu et al., 2023; O. Traxer et al., 2019), with approximately one-third being randomized controlled trials (Gupta et al., 2025; Christopher R. Haas et al., 2023; Shello et al., 2025; Pathak et al., 2023). Sample sizes varied considerably, from 12 patients (Lazarus et al., 2025) to 6,663 patients (Gauhar et al., 2023), with most studies including 50-300 patients. Most studies used non-contrast computed tomography (CT) as the primary imaging modality for preoperative evaluation. Imaging parameters most frequently analyzed included stone density measured in Hounsfield units (HU), stone size, stone burden, and anatomical location within the collecting system (Sergeev et al., 2023; A. I. Tursunov et al., 2022).

Laser Technology Comparison

nmStudies employed various laser technologies, predominantly holmium: YAG (Ho: YAG) and thulium fiber laser (TFL), with differing power settings and fragmentation techniques.

Table 1. Laser Technology Comparison

Technology	Power Settings	Technique	Key Findings
Ho: YAG low power	20-35 W	Dusting, fragmentation	Effective for routine cases
Ho: YAG high-power	60-120 W	Dusting, fragmentation, Moses mode	Reduced operative time, better SFR
Thulium fiber laser	50-60 W	Dusting, popcorning	Shorter lasing time, less retropulsion
Moses technology	Various	Contact mode, pulse modulation	Reduced fragmentation time, less retropulsion
Vapor Tunnel	1 J, 12 Hz	Long pulse dusting	Complete dusting, reduced energy

Stone Density as a Predictor

Stone density, measured as Hounsfield units on CT, emerged as a significant predictor across multiple studies, though its influence varied by stone location and size. One retrospective study of 152 patients using Vapor Tunnel Ho:YAG demonstrated significantly decreased laser time, operative time, and energy consumption in stones <1000 HU compared to >1000 HU (Luis Rico et al., 2024). The initial stone-free rate was markedly different: 40% for hard stones versus 95% for non-hard stones after a single session ($p=0.01$) (El Hamed et al., 2017). Operative times were also significantly longer for hard stones (75±15 vs 55±13 minutes, $p<0.01$) (El Hamed et al., 2017). Sixty percent of patients with hard stones required a second session compared to only 4.8% of those with non-hard stones ($p=0.01$) (El Hamed et al., 2017).

A predictive model was developed incorporating both stone size and density: the SMASH score (Hounsfield units × stone maximum size in cm/100) (Perri et al., 2024). Using a cut-off of 15, this score guided treatment selection between RIRS and mini-PCNL for stones 10-20 mm (Perri et al., 2024). For RIRS, stones with SMASH <15 achieved 82% stone-free rate versus 61% for SMASH ≥15 ($p=0.03$) (Perri et al., 2023), while mini-PCNL showed comparable results regardless of score (75% vs 85%, $p=0.32$) (Perri et al., 2023).

Stone Size and Volume as Predictors

Stone size and volume consistently predicted both laser efficiency and stone-free outcomes across diverse clinical contexts. In a multicenter study of 704 patients undergoing flexible ureteroscopy with FANS, stone volume was identified as a negative predictor of stone clearance in multivariate analysis (OR 0.76-0.81, $p \leq 0.005$) (Gauhar et al., 2025). Larger stones (>2 cm) were associated with longer operative times: in the popcorning group, lasing time was 17 minutes and total operative time 50 minutes versus 14 and 44 minutes respectively in the dusting group with smaller stones (Gauhar et al., 2025). Stone volume was positively correlated with both laser energy ($R^2=0.823$ for Moses laser, $R^2=0.693$ for Raykeen laser) and lithotripsy time ($R^2=0.800$ for Moses, $R^2=0.678$ for Raykeen) (Haitao Liu et al., 2024). This correlation remained independent of stone density (Haitao Liu et al., 2024).

For larger stones, efficiency declined substantially. A prospective study comparing high-frequency dusting versus low-frequency fragmentation for stones >2 cm found that only 73.3% of patients could be completely cleared after a single session with dusting (A. Singh et al., 2017), while fragmentation achieved stone-free status in only 50% of cases (A. Singh et al., 2017). In contrast, for stones <2 cm, a randomized trial achieved 95.8% stone-free rate using variable laser settings (C. Vaddi et al., 2020).

Stone Location Influence

Stone location significantly affected both laser efficiency and stone-free outcomes, with lower pole stones presenting particular challenges. A multicenter analysis of 6,663 patients found that lower pole stones were associated with higher residual fragments and complications on multivariate analysis (Gauhar et al., 2023). In bilateral stone treatment, lower pole location was associated with lower odds of bilateral stone-free status (OR 0.523, 95% CI 0.381-0.719, $p<0.001$) (Chai et al., 2024). A prospective randomized study of 68 patients evaluated stone relocation from the lower pole to a favorable calyx before lithotripsy versus in situ treatment for 10-20 mm stones (A. Shrestha et al., 2022). Primary stone-free rate at 1 day was also higher with relocation (82.2% vs 66.7%) (Ru Huang et al., 2024). For lower calyceal stones specifically, a retrospective study of 216 patients found that stone basket use combined with flexible ureteroscopy significantly improved outcomes (D. Jinhua et al., 2022).

However, stone location effects interacted with treatment modality. When comparing RIRS to mini-PCNL for stones 10-20 mm using the same laser (Fiber Dust), higher stone-free rates were achieved for upper calyceal stones with RIRS (90.4%) but for lower calyceal stones with mini-PCNL (91.6%) (Perri et al., 2022).

Imaging Parameters and Predictive Models

Beyond stone density and size, several studies evaluated additional imaging parameters and developed integrated predictive models. In a study of 60 patients, infundibular pelvic angle was measured, with mean values of 53.87 degrees in stone-free patients versus 50.33 degrees in those with residual fragments (Aksoy et al., 2022). However, the statistical significance of this difference was not explicitly stated. Distance-based measurements showed predictive value in semi-rigid ureteroscopic lithotripsy. For proximal ureteral stones, the distance from the stone to the ureteropelvic junction was significantly higher in patients who achieved stone-free status ($p=0.006$) (Okçelik et al., 2021). This anatomical parameter helped predict procedural success independent of stone characteristics.

The SMASH scoring system (Hounsfield units × stone maximum size in cm/100) represented the most comprehensive imaging-based predictive model identified (Perri et al., 2024). Applied to 350 patients with renal stones 10-20 mm (Perri et al., 2024), a cut-off of 15 distinguished patient groups with different optimal treatments. For RIRS, patients with SMASH <15 had significantly higher stone-free rates (82%) compared to those with SMASH ≥15 (61%, $p=0.03$) (Perri et al., 2023), while mini-PCNL outcomes were comparable across score groups (Perri et al., 2023). Mean total operative time with RIRS was 52.3 minutes for SMASH <15 versus 63.7 minutes for SMASH ≥15 (Perri et al., 2024).

Laser Efficiency Metrics Across Technologies

Laser efficiency was measured using multiple metrics. For thulium fiber laser versus Ho:YAG comparison, a prospective randomized study of 126 patients found TFL significantly reduced operative time (45.77±15.67 vs 52.79±18.11 minutes, p=0.031) and laser usage time (29.84±13.32 vs 36.39±15.75 minutes, p=0.024) (B. Kozubaev et al., 2025). Another prospective study of 180 patients confirmed shorter operative time with TFL (18.5±1.5 vs 31.6±1.2 minutes, p=0.024) and lasing time (7.4±1.8 vs 14.8±1.5 minutes, p=0.011) (Chandramohan et al., 2023), with better laser efficacy and ablation speed (both statistically significant) (Chandramohan et al., 2023). Stone-free rate at 30 days was 100% for TFL versus 94.3% for Ho:YAG (A. Martov et al., 2020).

Ablation efficiency calculations reported 25.7 J/mm³ for Moses technology versus 30 J/mm³ for TFL (p=0.98), with speeds of 1.1 mm³/sec versus 0.89 mm³/sec (p=0.26) (Jessica Lange et al., 2025). In another randomized trial comparing fragmentation versus dusting with TFL, fragmentation mode achieved significantly higher ablation speed (0.405 vs 0.17 mm³/sec, p<0.001) despite shorter lasing time (20.5 vs 34.25 minutes, p<0.001) (Pathak et al., 2023). Stone fragmentation efficiency (volume/laser working time) was calculated in a study of 216 patients, showing Moses achieved 137.86 mm³/min versus 114.94 mm³/min for regular dusting mode (p<0.001) (Wang et al., 2021), associated with shorter laser working time (4.99±1.06 vs 5.94±0.96 minutes, p<0.001) (Wang et al., 2021).

Dusting Versus Fragmentation Strategies

The choice between dusting and fragmentation techniques showed divergent effects on efficiency and outcomes. A prospective randomized study of 100 patients with renal calculi compared low-energy high-frequency dusting (0.3-0.5 J, 15-20 Hz) versus higher-energy fragmentation (1-1.2 J, 6-10 Hz) with basket retrieval (El-Nahas et al., 2019). Operative time was significantly shorter with dusting (76 vs 91 minutes, p=0.009) (El-Nahas et al., 2019), but the stone-free rate was significantly better with fragmentation (78.6% vs 58.6%, p=0.035) (El-Nahas et al., 2019). The need for secondary procedures was comparable (23.3% vs 33.3%, p=0.244) (El-Nahas et al., 2019).

For large stones 2-3 cm, a randomized trial of 230 patients compared conventional (basketing + dusting) versus Moses (pop-dusting) techniques (Xiaodong Hao et al., 2024). Moses mode required higher energy consumption (119.3±15.2 vs 92.8±15.1 kJ, p<0.001) (Xiaodong Hao et al., 2024) but achieved shorter operation time for isolated stones (99.6±17.5 vs 111.4±10.7 minutes, p<0.001) (Xiaodong Hao et al., 2024). Stone-free rates were similar between techniques (Xiaodong Hao et al., 2024). In contrast, a study specifically comparing dusting (popcorning 95.6%, minimal basket used 4.4%) with FANS versus fragmentation with traditional sheath (basketing 40.0%, popcorning 64.4%) found dusting with FANS achieved significantly higher 100% stone-free rate (80.0% vs 13.3%) (Ong et al., 2024) despite longer operative times (65 vs 55 minutes) (Ong et al., 2024).

A 60-patient randomized trial using thulium fiber laser at fixed low-power settings compared dusting versus fragmentation for upper tract stones 10-20 mm (Pathak et al., 2023). Fragmentation mode showed significantly shorter lasing time (20.5 vs 34.25 minutes, p<0.001) and higher ablation speed (0.405 vs 0.17 mm³/sec, p<0.001) (Pathak et al., 2023), though stone-free rates were comparable (Pathak et al., 2023).

Stone-Free Rate Outcomes

BMI and Patient-Specific Factors

Body mass index emerged as an unexpected positive predictor of stone-free rate in flexible ureteroscopy. In a randomized trial of 100 patients with kidney stones 5-20 mm, multivariate analysis revealed higher BMI was associated with better stone-free rate (OR 1.17, 95% CI 1.02-1.34, p=0.022) (Albert et al., 2022; Meller et al., 2025; Meller et al., 2022). A retrospective analysis of 309 operations across four BMI groups (normal, overweight, obese, morbidly obese) found no differences in operative time, hospital stay, stone-free rates (81-87.4%), or complications (12-16%) (E. Alkan et al., 2015), demonstrating RIRS efficiency was independent of BMI (E. Alkan et al., 2015). Age also influenced outcomes; age was associated with lower odds of bilateral stone-free status (OR 0.979, 95% CI 0.965-0.994, p=0.006) (Chai et al., 2024), alongside lower pole location and stone diameter (Chai et al., 2024).

Equipment and Access Sheath Technologies

Flexible and navigable suction ureteral access sheath (FANS) technology demonstrated improvements over conventional sheaths. A prospective multicenter study of 394 patients found FANS achieved high overall stone-free rates of 97.5% in non-pre-stented patients and 97.0% in pre-stented patients (Jahrreiss et al., 2024). FANS was associated with shorter operative times (55.25 vs 61.36 minutes, p=0.028) and significantly higher stone-free rate at one month (95% vs 67%, p<0.005) (Cacciatore et al., 2025), with fewer reinterventions (p=0.02) (Cacciatore et al., 2025) and lower postoperative complications (Cacciatore et al., 2025). For end-fire flexible negative-pressure UAS (F-UAS) in 2-3 cm kidney stones, a retrospective case-control study of 268 patients found F-UAS improved stone clearance rate (91.9% vs 81.8%, p=0.014) and reduced operation time (51.0±13.9 vs 59.8±18.2 minutes, p<0.001) (Chenglong Wu et al., 2025) compared to traditional UAS.

Power Settings and Laser Modulation

Power settings showed complex relationships with outcomes, varying by stone characteristics and clinical context. A randomized trial of 150 patients comparing high-power (16-18 W) versus low-power (4-6 W) thulium fiber laser for 8-25 mm renal stones found no difference in operative time (HP: 48 vs LP: 54 minutes, p=0.12) (Æsøy et al., 2025), but high-power used more energy (12 vs 7 kJ, p<0.001) with shorter active laser time (13 vs 24 minutes, p<0.001) (Æsøy et al., 2025).

For high versus low pulse energy dusting protocols using Ho:YAG, a prospective randomized study of 174 patients found high pulse energy (1.2-2.5 J, 8 Hz) resulted in more rapid dusting and reduced operative time compared to low pulse energy (<0.5 J, ≥15 Hz) (M. Elshazly et al., 2024), without affecting stone-free rate (M. Elshazly et al., 2024).

Pulse modulation technologies showed benefits. The Virtual Basket technology, using pulse modulation to create vapor channels (Bozzini et al., 2021), was associated with significantly lower fragmentation time for both ureteral stones (16.1 vs 20.4 minutes, p<0.05) and renal stones (19.8 vs 28.7 minutes, p<0.05) (Bozzini et al., 2021), with reduced total procedural time and retropulsion (Bozzini et al., 2021).

Complications and Safety Outcomes

Complication rates were generally low across studies, with most complications classified as Clavien-Dindo Grade I-II. In a prospective study of 124 interventions, acute pyelonephritis occurred in 1.8% of single stone cases and 4.4% of multiple stone cases, with remaining complications not exceeding Grade I (V. Sergeev et al., 2023). A high-power laser study of 284 patients reported more infectious complications in the low-power group (n=7) compared to high-power group (n=3) (A. Pietropaolo et al., 2022), though overall complication rates were comparable (A. Pietropaolo et al., 2022).

For FANS technology, a study of 394 patients reported only low-grade Traxer grade 1 ureteric injuries in 4.3% of non-pre-stented patients versus 0.4% of pre-stented patients (p=0.021) (Jahrreiss et al., 2024), with no sepsis in either group (Jahrreiss et al., 2024). Ureteric injury related to sheath placement was observed exclusively in the dusting group in one study (6.8% vs 0%) (Gauhar et al., 2025), while another study using vacuum suction catheter semi-rigid ureteroscopy reported significantly lower fever rates (2.1% vs 17.0%, p=0.015) and stone retropulsion (6.3% vs 21.3%, p=0.033) (Xing-Huan Wang et al., 2024).

Hospital length of stay was generally short, with median stays typically 1-3 days (Gauhar et al., 2024; V. Sergeev et al., 2023; Erol et al., 2024). High-power laser use was associated with reduced hospitalization duration (1.42±1.10 vs 2.35±2.27 days, p<0.001) (Erol et al., 2024). The use of FANS allowed discharge within 24 hours for all patients in one study (Gauhar et al., 2023).

Stone Density Prediction Domains

The evidence reveals important distinctions in when and how imaging parameters predict laser lithotripsy outcomes, with predictive utility varying substantially by stone density thresholds, size categories, and anatomical location. Stone density (measured in Hounsfield units) demonstrates clear predictive value, but its influence appears confined to specific density ranges and stone locations. For renal pelvic stones 2-3 cm in size, the HU >1000 versus <1000 threshold creates distinct efficiency profiles: stones below 1000 HU achieved 95% initial stone-free rate with operative time of 55±13 minutes, while those above 1000 HU achieved only 40% with 75±15 minutes (p<0.01) (El Hamed et al., 2017; Chandramohan et al., 2023). This density threshold also affected retreatment, with 60% of hard stones requiring second sessions versus 4.8% of non-hard stones (El Hamed et al., 2017). The mechanistic explanation appears straightforward: denser stones require more laser energy for equivalent fragmentation, extending both active lasing time and total operative time.

However, this density effect diminishes for smaller stones and different anatomical locations. For impacted upper ureteral stones, no correlation existed between density and laser energy or lithotripsy time (Haitao Liu et al., 2024). In flexible ureteroscopy for 5-20 mm stones, density failed to predict stone-free rate on multivariate analysis (p=0.884) (Albert et al., 2022), while BMI surprisingly emerged as the only significant predictor (Albert et al., 2022; Meller et al., 2025).

The SMASH score integration of both density and size (HU × size in cm/100) may reconcile these findings by accounting for total stone burden requiring fragmentation. The score's cut-off of 15 successfully distinguished RIRS success rates (82% vs 61%, p=0.03) (Perri et al., 2023), suggesting density alone is insufficient—its predictive value emerges through interaction with stone volume.

Table 2. Summary of Imaging Predictors and Outcomes Categorized by Laser Modality (Ho: YAG vs. TFL)

Imaging Parameter	Laser Modality	Impact on Laser Efficiency	Impact on Stone-Free Rate (SFR)	Clinical Implications & Thresholds
Stone Density (HU)	Holmium:YAG (Ho:YAG)	Significantly prolongs lasing and operative time; increased retreatment risk for high-density stones.	Lower single-session SFR in high-density stones, particularly above 1000 HU (40% vs 95%).	Stones >1000 HU require high-power settings, risking thermal injury.
	Thulium Fiber Laser (TFL)	Minimal impact on efficiency; high-frequency dusting maintains speed in hard stones.	Maintains high SFR across all density levels due to superior fine-dusting capabilities.	Density limitations are largely mitigated; ideal for hard calcium oxalate stones.

Imaging Parameter	Laser Modality	Impact on Laser Efficiency	Impact on Stone-Free Rate (SFR)	Clinical Implications & Thresholds
Stone Size & Volume	Holmium:YAG (Ho:YAG)	Energy requirements scale exponentially; increased risk of stone migration.	SFR drops significantly for stones >20 mm (68% vs 100%).	Success drops to 25% for cumulative diameter >30 mm.
	Thulium Fiber Laser (TFL)	Rapid ablation rate minimizes overall surgical duration for larger volumes.	Achieves higher single-session SFR for stones >20 mm compared to Ho:YAG.	Facilitates RIRS for borderline large stones (15–25 mm).
Anatomical Location (Lower Pole)	Holmium:YAG (Ho:YAG)	Fiber stiffness impairs scope deflection, limiting energy delivery.	Significantly reduced SFR (OR 0.523) due to poor clearance of fragments.	Requires specialized nitinol baskets and strict IPA evaluation.
	Thulium Fiber Laser (TFL)	Highly flexible thin fibers (150 µm) allow maximum deflection without energy loss.	Higher clearance and SFR in lower pole calyces, especially when combined with suction.	Overcomes unfavorable anatomy; reduces physical footprint in working channel.

Size-Dependent Efficiency Boundaries

Stone size demonstrates non-linear effects on efficiency and outcomes, with apparent thresholds around 15-20 mm where single-session stone-free rates decline precipitously. For stones <10 mm, technologies showed minimal differentiation, with stone-free rates exceeding 90% regardless of laser type or technique (Xu et al., 2023; Md. Shahidul Islam et al., 2022; Abushnaf et al., 2023). Between 10-20 mm, efficiency metrics begin diverging: high-power lasers maintained shorter operative times (66.17 vs 88.70 minutes, p<0.001) (Erol et al., 2024), while achieving comparable stone-free rates to low-power systems (Erol et al., 2024).

Beyond 20 mm, single-session efficacy deteriorates sharply. For stones >20 mm, initial stone-free rate dropped to 68% versus 100% for stones ≤20 mm at 1 month follow-up (Abushnaf et al., 2023), with mean operative time extending from 49 minutes to 94.9 minutes (Abushnaf et al., 2023). For bilateral cases with total diameter >30 mm, first-procedure stone-free rate was only 25.0% compared to 73.9% for ≤30 mm (p<0.001) (Tu et al., 2023), requiring repeat procedures in 75% versus 26% (Tu et al., 2023).

This size effect reflects both the volume of stone requiring fragmentation and the technical challenges of fragment management. Larger stones generate more residual fragments: for stones 2-3 cm, fragmentation with basketing achieved 78.6% stone-free rate versus only 58.6% with dusting alone (p=0.035) (El-Nahas et al., 2019).

Location-Specific Anatomical Constraints

Lower pole location consistently predicts reduced stone-free rates across multiple studies, independent of size or density. Multivariate analyses confirmed lower pole as an independent negative predictor (OR 0.523, p<0.001 for bilateral cases) (Chai et al., 2024) and as a factor reducing stone clearance rate (p=0.006) (Tai et al., 2018). However, the predictive magnitude varies by intervention: relocation of lower pole stones before lithotripsy improved 3-month stone-free rate from 84.4% to 97.8% (p=0.026) (Ru Huang et al., 2024), suggesting the anatomical disadvantage is potentially modifiable through technique.

The lower pole effect appears mechanistically related to dependent drainage and gravitational retention of fragments. Studies using active retrieval strategies (basket extraction, stone relocation to non-dependent areas, or specialized access sheaths with suction) showed attenuated location effects. With FANS technology achieving 94.7% stone-free rate for varied stone locations and volumes (Gauhar et al., 2023), the lower pole disadvantage may reflect technical approach rather than immutable anatomy.

For upper calyceal versus lower calyceal stones treated with RIRS versus mini-PCNL, location predicted optimal modality: RIRS achieved 90.4% stone-free rate for upper calyceal stones, while mini-PCNL achieved 91.6% for lower calyceal stones (Perri et al., 2022). This suggests anatomical access routes create location-specific efficiency differences.

Technology and Technique Interactions

The predictive value of imaging parameters appears modulated by laser technology and technique. While stone volume negatively predicted stone-free rate across studies (Gauhar et al., 2025; Xiaodong Hao et al., 2024), this effect was reduced when using thulium fiber laser. Multivariable analysis confirmed TFL use increased odds of achieving zero residual fragments (OR 1.95, 95% CI 1.01-3.82) (Gauhar et al., 2024) and was associated with higher odds of bilateral stone-free status (OR 1.686, p=0.041) (Chai et al., 2024).

The dusting versus fragmentation decision interacts with stone size and location. For stones <15 mm in non-dependent locations, dusting alone achieved 95.8% stone-free rate (C. Vaddi et al., 2020), with shorter operative times (El-Nahas et al., 2019). However, for stones >15 mm or in lower pole locations, active fragmentation with basketing improved stone-free rates from 58.6% to 78.6% (p=0.035) (El-Nahas et al., 2019), despite longer operative times (El-Nahas et al., 2019). This suggests imaging-based stone size and location can guide technique selection.

High-power versus low-power laser selection shows counterintuitive outcomes. While high-power (16-18 W) TFL shortened active laser time (13 vs 24 minutes) (Æsøy et al., 2025), it paradoxically reduced stone-free rates (Grade A: 44% vs 63%, p=0.02) (Æsøy et al., 2025) and increased minor complications (37% vs 11%, p<0.001) (Æsøy et al., 2025). This may reflect thermal tissue effects or fragment scattering at higher power levels, suggesting optimal power exists as a function of stone volume and location rather than a universal maximum.

Validated Predictors Versus Promising Indicators

Based on consistent findings across multiple studies with adequate statistical control, established predictors of laser efficiency and stone-free outcomes include:

a) Stone density >1000 HU for stones >2 cm predicts reduced single-session stone-free rate (El Hamed et al., 2017; Chandramohan et al., 2023) and increased operative time (El Hamed et al., 2017; Rico et al., 2024)
b) Stone size >20 mm predicts reduced stone-free rate (Abushnaf et al., 2023) and need for staged procedures (Tu et al., 2023)
c) Lower pole location independently predicts reduced stone-free rate (Chai et al., 2024; Tai et al., 2018)
d) Higher BMI predicts improved stone-free rate in flexible ureteroscopy (Albert et al., 2022; Meller et al., 2025)
e) Stone volume inversely correlates with stone-free rate (Gauhar et al., 2025) and positively correlates with laser time and energy (Haitao Liu et al., 2024)

Promising indicators requiring further validation include:

a) SMASH score (HU × size/100) with cut-off of 15 for procedure selection (Perri et al., 2023; Perri et al., 2024)
b) Distance from stone to ureteropelvic junction affecting semi-rigid ureteroscopy success (Okçelik et al., 2021)
c) Infundibular pelvic angle for lower pole stones (Aksoy et al., 2022)
d) Cumulative stone burden >150 mm² predicting reduced clearance (Tai et al., 2018)

Evidence Gaps for AI Prediction Models

Current studies lack standardized imaging protocols, with density measurement techniques unspecified in most reports (Gauhar et al., 2025; Gauhar et al., 2024; Xu et al., 2023). No studies employed automated volumetric segmentation or three-dimensional shape analysis, features readily extractable for machine learning models. Stone location was categorized anatomically (lower pole, upper pole, pelvis) without quantitative metrics of calyceal geometry, infundibular length, or pelvicalyceal angles that could inform access difficulty predictions.

Most studies treated stone parameters as independent predictors without examining interactions. The few that assessed combinations (SMASH score, stone volume with age) suggest multiplicative effects exist but remain underexplored. Advanced imaging features—stone heterogeneity, surface irregularity, composition beyond density, proximity to collecting system—were rarely assessed despite potential relevance to fragmentation behavior.

Laser efficiency metrics lacked standardization. “Lasing time” definitions varied between total laser activation time (Xu et al., 2023) and time excluding pauses (Wang et al., 2021), while ablation efficiency calculations used different denominators (J/mm^3 versus mm^3/J) (Jessica Lange et al., 2025; El-Nahas et al., 2019). No studies prospectively validated imaging-based algorithms for predicting these efficiency metrics, representing a critical gap for AI model development.

Stone-free rate definitions were heterogeneous, ranging from zero fragments (Gauhar et al., 2024; Gupta et al., 2025) to <4 mm residuals (Perri et al., 2024; Zeinelabden et al., 2024; Mulk et al., 2025), assessed at timepoints from 24 hours (Fattah et al., 2024) to 1 year (Hemo et al., 2025). This variability complicates outcome prediction model training and limits meta-analytic synthesis. Standardized stone-free criteria with imaging-confirmed volumetric assessment would enable more robust predictive modeling.

Notably absent were prospective studies validating imaging-based prediction tools in independent cohorts. While several studies identified predictors through multivariable regression (Gauhar et al., 2025; Chai et al., 2024; Meller et al., 2025), none performed external validation or assessed model calibration and discrimination in new patient populations—essential steps for clinical AI implementation.

Discussion

The comparative synthesis of laser modalities reveals that the traditional impact of preoperative imaging parameters is fundamentally altered by technological advancements. For decades, Holmium:YAG (Ho:YAG) has been the gold standard, yet its performance remains tightly bound to stone characteristics. High stone density (>1000 HU) Ho:YAG lithotripsy extended operative times and increased thermal energy dissipation (El Hamed et al., 2017). Furthermore, large stone size (>20 mm) combined with Ho:YAG fragmentation often induces high retropulsion, forcing the surgeon to repeatedly reposition the scope, which lowers procedural efficiency and compromises the single-session stone-free rate (SFR) (Abushnaf et al., 2023; Tu et al., 2023).

Conversely, the emergence of Thulium Fiber Laser (TFL) technology introduces a higher water absorption coefficient and ability to operate at ultra-high frequencies (up to 2000 Hz) with very low pulse energies a paradigm shift in how imaging predictors dictate surgical outcomes. Due to its, TFL excels at 'dusting' rather than fragmenting. This qualitative synthesis demonstrates that TFL minimizes the clinical relevance of high Hounsfield Units, maintaining high-speed ablation even in stones exceeding 1000 HU. Because TFL produces sub-millimeter particles, the retropulsion effect is practically eliminated. Consequently, the predictive weight of large stone volume on lower SFR is substantially mitigated when TFL is utilized, as the fine dust is easily washed out or aspirated, bypassing the multi-stage requirements often seen with traditional Ho:YAG protocols (Singh et al., 2017).

Stone Density: Threshold Effects and Context Dependence

Stone density measured in Hounsfield units (HU) as a significant predictor but reveals important context dependence. Our synthesis confirms that density plays an important role in determining fragmentation efficiency, particularly for larger renal stones.

For renal pelvic stones >2 cm, the 1000 HU threshold clearly distinguishes outcomes: stones below 1000 HU achieved 95% initial stone-free rate with operative time 55±13 minutes, while those above 1000 HU achieved only 40% with 75±15 minutes ($p<0.01$) (El Hamed et al., 2017). Importantly, this difference translated into a substantially higher need for secondary procedures, with repeat intervention required in approximately 60% of patients with high-density stones compared with less than 5% among lower-density stones (El Hamed et al., 2017). Mechanistically, denser stones require greater energy for equivalent fragmentation, directly extending both active lasing time and total operative time (Luis Rico et al., 2024; Wang et al., 2021).

However, this density effect diminishes for smaller stones and different locations. Studies examining impacted ureteral stones have reported no significant association between density and laser energy requirements or lithotripsy time (Haitao Liu et al., 2024). Similarly, in flexible ureteroscopy for 5-20 mm stones, multivariate analysis showed density did not influence stone-free rate ($p=0.884$) (Albert et al., 2022; Meller et al., 2025), while BMI surprisingly emerged as the only significant predictor (Albert et al., 2022; Meller et al., 2025). These findings suggest that density should not be interpreted in isolation but rather in the context of stone burden and anatomical factors.

Stone Size: Non-Linear Thresholds and Clinical Implications

Stone size demonstrates clear non-linear effects on outcomes, with apparent thresholds at 15-20 mm where single-session stone-free rates decline substantially. Stones smaller than 10 mm typically achieve stone-free rates exceeding 90% regardless of laser technology or operative strategy (Xu et al., 2023; Comparative Study Between Holmium Laser Versus Pneumatic Lithotripsy for the Treatment of Lower Ureteric Calculi, 2022; Abushnaf et al., 2023). Stone size 10–20 mm range, the intermediate category: high-power lasers maintained shorter operative times (66.17 vs 88.70 minutes, $p<0.001$) (Erol et al., 2024), while achieving comparable stone-free rates (Erol et al., 2024).

Beyond 20 mm, single-session efficacy deteriorates sharply. Studies reported reducing stone-free rates 68% versus 100% and longer operative times from 49 to 94.9 minutes in this population, reflecting the increased fragmentation burden and the challenges associated with managing larger volumes of residual fragments (Abushnaf et al., 2023). For bilateral cases with total diameter >30 mm, first-procedure stone-free rate may fall to approximately 25%, frequently necessitating staged procedures (Gauhar et al., 2025; El-Nahas et al., 2019; Tu et al., 2023). These observations emphasize that stone size functions not only as a marker of fragmentation difficulty but also as a determinant of fragment clearance and procedural complexity. Larger stones generate a greater number of fragments, increasing the need for basketing, irrigation management, and extended operative time.

Integrated Imaging Models: Toward Multivariable Prediction

Given the limitations of individual predictors, several studies have explored integrated models combining multiple imaging parameters. The SMASH score (HU × stone maximum size in cm/100) represents one of the most promising approaches identified in this review (Perri et al., 2024). By combining stone density and stone size into a single composite metric the SMASH score attempts to quantify overall fragmentation burden (Perri et al., 2023).

Using a cut-off of 15, suggest that this score can distinguish patient groups with significantly different probabilities of successful retrograde intrarenal surgery. Lower scores achieved stone-free rates of approximately 82%, whereas those with higher scores demonstrated success rates closer to 61% (Perri et al., 2023). Low-to-moderate score indicates that the stone burden is highly amenable to RIRS, promising an optimal SFR without exposing the patient to the higher morbidity risks associated with percutaneous access. When higher-score burdens, mini-PCNL as the primary approach can maximize the stone clearance with maximal single-session. By implementing the differences of SMASH score, suggesting that integrated imaging scores may also assist in procedure selection.

Technology Interactions Modifying Imaging Predictors

Advanced endourological technologies, specifically the Thulium Fiber Laser (TFL) and Flexible and Navigable Suction Ureteral Access Sheaths (FANS), have neutralized unfavorable anatomy and adverse stone morphology. Historically, a lower pole stone location presented a major therapeutic obstacle; a narrow infundibulopelvic angle (IPA) severely limited flexible ureteroscope deflection, while stiff Ho:YAG laser fibers compromised scope longevity and energy delivery (Kozubaev et al., 2025; Chandramohan et al., 2023; Tg et al., 2025; Elgebaly et al., 2021). In potential studies the TFL compared to conventional holmium:YAG systems had considerably reduced operative and lasing times with comparable stone free rates and complications (Chai et al., 2024; B. Kozubaev et al., 2025; Chandramohan et al., 2023; Pathak et al., 2023).

Simultaneously, the integration of FANS redefines fragment clearance. Traditional retrograde approaches rely on passive irrigation or tedious basket extraction, which is highly inefficient for lower pole stones (Elgebaly et al., 2021). FANS addresses this by generating continuous, controlled negative intrarenal pressure. As the high-frequency TFL reduces stones to fine dust, the FANS continuously evacuates these micro-fragments in real-time (Jahrreiss et al., 2024; Ong et al., 2024; A. Singh et al., 2017). These technologies may partially mitigate unfavorable imaging predictors by improving fragment clearance and reducing intrarenal pressure.

Implications for AI Model Development

Current evidence provides a foundation for AI model development while identifying critical gaps. Validated predictors suitable for model inclusion include stone density >1000 HU (for stones >2 cm), stone size >20 mm, lower pole location, and stone volume. Promising but unvalidated indicators include SMASH score, distance from stone to ureteropelvic junction (Okçelik et al., 2021), infundibular pelvic angle (Aksoy et al., 2022), and cumulative stone burden >150 mm² (Tai et al., 2018). Preoperative CT imaging provides detailed information regarding stone density, size, volume, and anatomical location, offering a rich source of structured data for predictive modeling.

Standardization priorities for AI training include: (1) uniform stone-free definitions with imaging-confirmed volumetric assessment at standardized timepoints (1-3 months); (2) consistent efficiency metrics (lasing time, total operative time, energy consumption, ablation speed with standardized denominators); (3) quantitative anatomical measurements beyond categorical location; and (4) prospective validation in independent cohorts. Studies should incorporate automated segmentation and radiomic feature extraction to capture stone heterogeneity and surface characteristics not currently assessed.

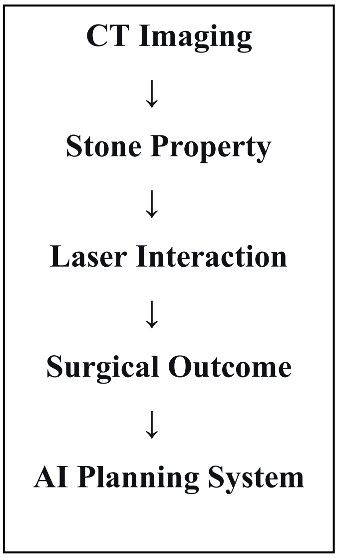

Figure 2. Concept Figure of This Systematic Review

Limitations

When interpreting the results of this review, it is important to recognize several limitations. The primary is heterogenicity across 110 including studies regarding imaging protocols and diagnostic equipment. Specifically, variability in computed tomography (CT) scanners—involving differences in slice thickness, tube voltage, and reconstruction algorithms—directly affects the consistency of Hounsfield Unit (HU) measurements across different centers. Secondaries, the definition of "stone-free rates" lacked standardization, ranging from the absolute absence of fragments to the presence of asymptomatic residual fragments under 3 mm or 4 mm. Lastly, because many primary studies did not explicitly differentiate outcomes between Ho:YAG and TFL technologies within their pooled analysis, a quantitative meta-analysis was precluded, limiting our ability to calculate precise effect sizes for each specific imaging predictor.

CONCLUSION

This systematic review of 110 studies establishes that preoperative imaging parameters predict laser efficiency and stone-free outcomes in endoscopic laser lithotripsy, with predictive utility varying by stone characteristics, anatomical location, and technology selection. Stone density >1000 HU predicts reduced single-session stone-free rates (40% vs 95%) and increased operative time (75±15 vs 55±13 minutes) for stones >2 cm, requiring second sessions in 60% versus 4.8% of cases (El Hamed et al., 2017). Stone size demonstrates non-linear effects with critical thresholds at 15-20 mm: stones >20 mm achieved only 68% initial stone-free rate versus 100% for stones ≤20 mm (Abushnaf et al., 2023), with first-procedure success of only 25.0% for bilateral total diameter >30 mm (Tu et al., 2023). Lower pole location independently predicts reduced stone-free rates (OR 0.523) (Chai et al., 2024), but relocation techniques improve 3-month stone-free rates from 84.4% to 97.8% (Ru Huang et al., 2024), indicating modifiability.

Technology selection modulates imaging-based predictions. Thulium fiber laser demonstrates shorter lasing time (7.4±1.8 vs 14.8±1.5 minutes) (Chandramohan et al., 2023) and increased odds of zero residual fragments (OR 1.95) (Gauhar et al., 2024). Moses technology improves fragmentation efficiency (137.86 vs 114.94 mm^3/min) (Wang et al., 2021). Flexible and navigable suction ureteral access sheath (FANS) achieves 94.7-97.5% stone-free rates (Gauhar et al., 2023; Jahrreiss et al., 2024) and attenuates negative predictors. Integrated predictive models like the SMASH score (HU × size/100) with cut-off of 15 distinguish RIRS success rates (82% vs 61%) (Perri et al., 2023), supporting combined rather than univariate prediction.

Based on consistent evidence, we recommend: (1) routine preoperative CT assessment with measurement of stone density, maximum diameter, volume, and location; (2) for stones >2 cm with density >1000 HU, counsel patients regarding high likelihood of staged procedures (60% requiring second sessions) (El Hamed et al., 2017); (3) for stones >20 mm, plan for potential staged approach or consider alternative modalities (Abushnaf et al., 2023); (4) for lower pole stones, employ relocation techniques to improve stone-free rates (Ru Huang et al., 2024); (5) consider TFL for improved efficiency in high-volume or dense stones (B. Kozubaev et al., 2025; Chandramohan et al., 2023; Gauhar et al., 2024); (6) utilize FANS technology when available to improve stone-free rates and reduce complications (Gauhar et al., 2023; Jahrreiss et al., 2024; Cacciatore et al., 2025; Ong et al., 2024); and (7) apply the SMASH score for procedure selection between RIRS and mini-PCNL for stones 10-20 mm (Perri et al., 2023; Perri et al., 2024).

Critical evidence gaps requiring investigation include: (1) prospective validation of imaging-based prediction tools in independent cohorts; (2) development of standardized definitions for stone-free outcomes and efficiency metrics; (3) incorporation of quantitative anatomical measurements beyond categorical location; (4) evaluation of advanced imaging features (stone heterogeneity, surface characteristics) using automated segmentation and radiomics; (5) investigation of technology-predictor interactions in randomized designs; (6) external validation of the SMASH score and other integrated models; and (7) development and validation of machine learning algorithms incorporating multiple imaging parameters with demonstrated predictive utility. Addressing these priorities will enable personalized, imaging-guided surgical planning that optimizes outcomes while minimizing procedural morbidity and healthcare costs.

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