



Comparative Efficacy, Patient-Specific Predictive Factors, and Long-Term Safety of Extracorporeal Shockwave Lithotripsy for Urinary Calculi: A Systematic Review of Technical Optimization and Clinical Outcomes

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ABSTRACT

Introduction

Extracorporeal Shockwave Lithotripsy (SWL) remains a pivotal, non-invasive treatment modality for urolithiasis, having revolutionized the management of stone disease since its introduction in the 1980s (Preminger et al., 2024; Long & Matlaga, 2020). Despite its established role, the current clinical landscape sees SWL increasingly challenged by highly effective, though more invasive, endourological techniques such as Ureteroscopic Lithotripsy (URSL/RIRS) and Percutaneous Nephrolithotomy (PCNL). The enduring relevance of SWL hinges critically upon optimal patient selection and rigorous adherence to technical optimization protocols to maximize efficacy and minimize failure rates (Wang et al., 2020).

Methods

A systematic search compliant with the Preferred Reporting Items

for Systematic Reviews and Meta-Analyses (PRISMA) statement was performed, synthesizing outcomes from high-level evidence studies, including meta-analyses encompassing a minimum of 15 randomized controlled trials (RCTs) (Li et al., 2023; Mokhtari et al., 2023). Data were extracted for 12 clinical outcomes. The quality of comparative trials was assessed using the Cochrane Risk of Bias tool, version 2 (RoB 2) (Higgins et al., 2024; Minozzi et al., 2022).

Results

Efficacy and Logistics: Contemporary endourological treatments generally yield higher efficacy; URSL/PCNL result in significantly superior overall stone-free rates (SFRs) compared to SWL, especially for stones exceeding 10 mm and those located in the lower pole calyx (Wang et al., 2015). SWL is associated with a significantly greater need for retreatment procedures, with an Odds Ratio (OR) of 0.08 favoring URSL (Li et al., 2023). However, SWL maintains substantial logistical advantages, including a significantly shorter operating time (Standardized Mean Difference -29.314 minutes favoring SWL) and shorter hospital stay (Mean Difference 1.14 days longer for URSL) (Mohamed et al., 2023; Li et al., 2023).

Safety and Predictors: While overall complication rates are statistically similar across methods (Li et al., 2023), URSL carries a higher specific risk of perforation (OR 0.13 favoring SWL) (Mohamed et al., 2023). Successful SWL is highly predictable based on pre-treatment imaging, with optimal success linked to stone density $HU < 1000$ and $SSD < 10$ cm (Siddiqui & Ahmed, 2021; Türk et al., 2024; Ouzaid et al., 2014). Furthermore,

technical refinement, such as decreasing the shock wave rate to 60 to 90 shocks per minute, substantially improves stone fragmentation efficacy (Long & Matlaga, 2020).

Long-Term Safety: A significant association exists between SWL performed for nephrolithiasis and the development of new-onset hypertension, evidenced by an overall Relative Risk (RR) of 1.21 (95% CI 1.11–1.31) (Seo et al., 2021). This risk increases with the number of SWL sessions required (Rudnick et al., 2018).

Conclusion

Extracorporeal Shockwave Lithotripsy remains the optimal non-invasive intervention for highly favorable calculi (≤ 10 mm, low HU, short SSD), provided technical optimization is rigorously applied. For stones predicted to be resistant, early treatment pivot toward URSL or PCNL is warranted to maximize definitive stone clearance and to mitigate the potentially dose-dependent long-term risk of hypertension and the requirement for multiple auxiliary procedures.

Keywords: Extracorporeal Shockwave Lithotripsy, Urolithiasis, Stone-Free Rate, Hounsfield Unit, Skin-to-Stone Distance, Hypertension, Risk of Bias, Systematic Review.

INTRODUCTION

Background and Clinical Context

Extracorporeal Shockwave Lithotripsy (SWL) fundamentally changed the clinical approach to urolithiasis management after its introduction in the 1980s, establishing itself as the only truly non-invasive treatment option (Preminger et al., 2024; Wang et al., 2020). The procedure, which fragments kidney and ureteral stones using shockwaves delivered from outside the body, rapidly became the most common intervention globally (Long & Matlaga, 2020). However, over the past decade, technological advancements in flexible ureteroscopy (URS) and improvements in Percutaneous Nephrolithotomy (PCNL) techniques have intensified the competition, necessitating a critical re-evaluation of SWL's contemporary role (Wang et al., 2020).

The primary barrier to consistent SWL success lies in the heterogeneity of outcomes, which are contingent upon a complex interplay of patient factors (e.g., obesity), stone characteristics (e.g., size, density), and technical execution (e.g., shock rate, coupling) (Long & Matlaga, 2020; Resorlu & Ozyuvali, 2023). Maximizing efficacy and minimizing the failure rates—which often necessitate auxiliary procedures—requires rigorous adherence to evidence-based optimization strategies (Wang et al., 2020).

Objectives

This systematic review aims to provide an integrated synthesis of the current evidence surrounding SWL, specifically focusing on its comparative standing and optimization strategies. The objectives are four-fold:

1. To compare SWL against URSL/RIRS and PCNL across 12 specific outcomes, encompassing efficacy (SFR), safety (complications), and logistical measures (operating time, hospital stay).
2. To quantify the predictive influence of Stone Density (HU) and Skin-to-Stone Distance (SSD) derived from pre-treatment imaging, establishing clear clinical cut-offs for optimal candidate

selection.

3. To synthesize the current evidence regarding technical optimization protocols, including the impact of shock wave rate, energy ramping, and acoustic coupling (Long & Matlaga, 2020; Wang et al., 2020).
4. To assess the level of evidence confirming the long-term systemic risks associated with SWL, particularly the association between renal SWL and new-onset hypertension (HTN) (Seo et al., 2021; Rudnick et al., 2018).

Hypothesis and PICO Formulation

The central hypothesis is that optimized SWL, relying on rigorous patient selection guided by HU/SSD nomograms and employing slow shock rate protocols, is safe and effective for small, favorable stones, potentially yielding outcomes comparable to URSL while maintaining logistical superiority. Conversely, its utility declines sharply for resistant stones, and its application is associated with a quantifiable, dose-dependent risk of new-onset hypertension.

PICO Elements:

- **P (Population):** Patients (adults and children) presenting with renal or upper ureteral stones, typically ranging from 5 mm to 20 mm in size (Siddiqui & Ahmed, 2021).
- **I (Intervention):** Extracorporeal Shockwave Lithotripsy (SWL).
- **C (Comparison):** Ureteroscopic Lithotripsy (URSL/RIRS), Percutaneous Nephrolithotomy (PCNL), or variant SWL technical protocols.
- **O (Outcomes):** The 12 primary outcomes assessed are Overall Stone-Free Rate (SFR), Initial SFR, Total Complications, Auxiliary Procedures Rate, Retreatment Rate, Perforation Rate, Hematuria, Procedural Failure, Operating Time, Hospital Stay, Stone Size (analyzed as a difference between groups), and New-Onset Hypertension (HTN)/Chronic Kidney Disease (CKD) risk.

Research Gap and Novelty

Previous systematic reviews often focus narrowly, examining either comparative success rates or isolated technical factors (Wang et al., 2020; Long & Matlaga, 2020). There is a lack of recent, integrated evidence synthesis that simultaneously incorporates three critical clinical dimensions: the quantitative comparison against modern endourology (ORs/SMDs), the objective pre-treatment predictive thresholds (HU/SSD), and the long-term safety data (HTN risk). This review provides a comprehensive, integrated framework for treatment decision-making, offering objective, evidence-based cut-off values for identifying the ideal SWL candidate and establishing criteria for early procedural triage to endoscopy. This integrated synthesis is particularly novel in its focus on linking patient-specific predictive factors to the ultimate goal of mitigating the dose-dependent risk of hypertension associated with multiple SWL sessions (Seo et al., 2021).

METHODS

Study Protocol and Registration (PRISMA Compliance)

This systematic review was conducted in strict compliance with the methodology prescribed by the PRISMA guidelines, ensuring high standards of rigor and transparency in the synthesis and reporting of evidence (Wang et al., 2020).

Search Strategy and Eligibility Criteria

The literature search encompassed major biomedical databases, including PubMed, Google Scholar, Semantic Scholar, Springer, Wiley Online Library. Key search terms included combinations of "shockwave lithotripsy," "urolithiasis," "randomized controlled trial," "stone-free rate," "Hounsfield unit," "SSD," and "hypertension." The search focused on English-language articles, spanning the period from 1984 to the present, to capture both foundational studies and recent high-level evidence (Wang et al., 2020; Li et al., 2023).

Inclusion Criteria: The review included randomized controlled trials (RCTs), comparative prospective and retrospective cohort studies focusing on predictive factors, and existing high-

quality systematic reviews and meta-analyses. The inclusion criteria required reporting on human subjects with renal or ureteric calculi (Siddiqui & Ahmed, 2021). The final evidence base synthesized included a robust volume of primary data, synthesizing results from at least 15 valid studies comparing SWL to URS, RIRS, or PCNL (Li et al., 2023; Mokhtari et al., 2023).

Search Strategy

The keywords used for this research based PICO :

Element	Keyword 1	Keyword 2	Keyword 3	Keyword 4
Population (P)	Patients with urinary calculi	Kidney stone patients	Urolithiasis patients	Nephrolithiasis patients
Intervention (I) / Exposure (E)	Extracorporeal Shockwave Lithotripsy	Shockwave Lithotripsy	SWL	ESWL
Comparison (C)	Ureteroscopic Lithotripsy	Ureteroscopy (URS/RIRS)	Percutaneous Nephrolithotomy (PCNL)	Endourological procedures
Outcome (O)	Stone-free rate	Treatment efficacy	Predictive factors	Long-term safety

The Boolean MeSH keywords inputted on databases for this research are: (*"Patients with urinary calculi"* OR *"Kidney stone patients"* OR *"Urolithiasis patients"* OR *"Nephrolithiasis patients"*) AND (*"Extracorporeal Shockwave Lithotripsy"* OR *"Shockwave Lithotripsy"* OR *"SWL"* OR *"ESWL"*) AND (*"Ureteroscopic Lithotripsy"* OR *"Ureteroscopy (URS/RIRS)"* OR *"Percutaneous Nephrolithotomy (PCNL)"* OR *"Endourological procedures"*) AND (*"Stone-free rate"* OR *"Treatment efficacy"* OR *"Predictive factors"* OR *"Long-term safety"*)

Data Extraction and Outcome Measures

Data extraction was executed using standardized templates designed to capture detailed information on patient demographics, precise stone characteristics (location, size, HU, SSD), SWL technical variables (rate, energy), and all 12 defined outcomes. Quantitative data for meta-analysis, including Odds Ratios (OR), Standardized Mean Differences (SMD), Mean Differences (MD), and their associated 95% Confidence Intervals (CI), were extracted from previously published meta-analyses, ensuring the direct use of pooled results (Mohamed et al., 2023; Li et al., 2023).

Table 1. Article Search Strategy

Database	Keywords	Hits
Pubmed	("Patients with urinary calculi" OR "Kidney stone patients" OR "Urolithiasis patients" OR "Nephrolithiasis patients") AND ("Extracorporeal Shockwave Lithotripsy" OR "Shockwave Lithotripsy" OR "SWL" OR "ESWL" AND "Ureteroscopic Lithotripsy" OR "Ureteroscopy (URS/RIRS)" OR "Percutaneous Nephrolithotomy (PCNL)" OR "Endourological procedures") AND ("Stone-free rate" OR "Treatment efficacy" OR "Predictive factors" OR "Long-term safety")	13
Semantic Scholar	("Patients with urinary calculi" OR "Kidney stone patients" OR "Urolithiasis patients" OR "Nephrolithiasis patients") AND ("Extracorporeal Shockwave Lithotripsy" OR "Shockwave Lithotripsy" OR "SWL" OR "ESWL") AND ("Ureteroscopic Lithotripsy" OR "Ureteroscopy (URS/RIRS)" OR "Percutaneous Nephrolithotomy (PCNL)" OR "Endourological procedures") AND ("Stone-free rate" OR "Treatment efficacy" OR "Predictive factors" OR "Long-term safety")	251
Springer	("Patients with urinary calculi" OR "Kidney stone patients" OR "Urolithiasis patients" OR "Nephrolithiasis patients") AND ("Extracorporeal Shockwave Lithotripsy" OR "Shockwave Lithotripsy" OR "SWL" OR "ESWL") AND ("Ureteroscopic Lithotripsy" OR "Ureteroscopy (URS/RIRS)" OR "Percutaneous Nephrolithotomy (PCNL)" OR "Endourological procedures") AND ("Stone-free rate" OR "Treatment efficacy" OR "Predictive factors" OR "Long-term safety")	58
Google Scholar	("Patients with urinary calculi" OR "Kidney stone patients" OR "Urolithiasis patients" OR "Nephrolithiasis patients") AND ("Extracorporeal Shockwave Lithotripsy" OR "Shockwave Lithotripsy" OR "SWL" OR "ESWL") AND ("Ureteroscopic Lithotripsy" OR "Ureteroscopy (URS/RIRS)" OR "Percutaneous Nephrolithotomy (PCNL)" OR "Endourological procedures") AND ("Stone-free rate" OR "Treatment efficacy" OR "Predictive factors" OR "Long-term safety")	892
Wiley Online Library	("Patients with urinary calculi" OR "Kidney stone patients" OR "Urolithiasis patients" OR "Nephrolithiasis patients") AND ("Extracorporeal Shockwave Lithotripsy" OR "Shockwave Lithotripsy" OR "SWL" OR "ESWL") AND ("Ureteroscopic Lithotripsy" OR "Ureteroscopy (URS/RIRS)" OR "Percutaneous Nephrolithotomy (PCNL)" OR "Endourological procedures") AND ("Stone-free rate" OR "Treatment efficacy" OR "Predictive factors" OR "Long-term safety")	23

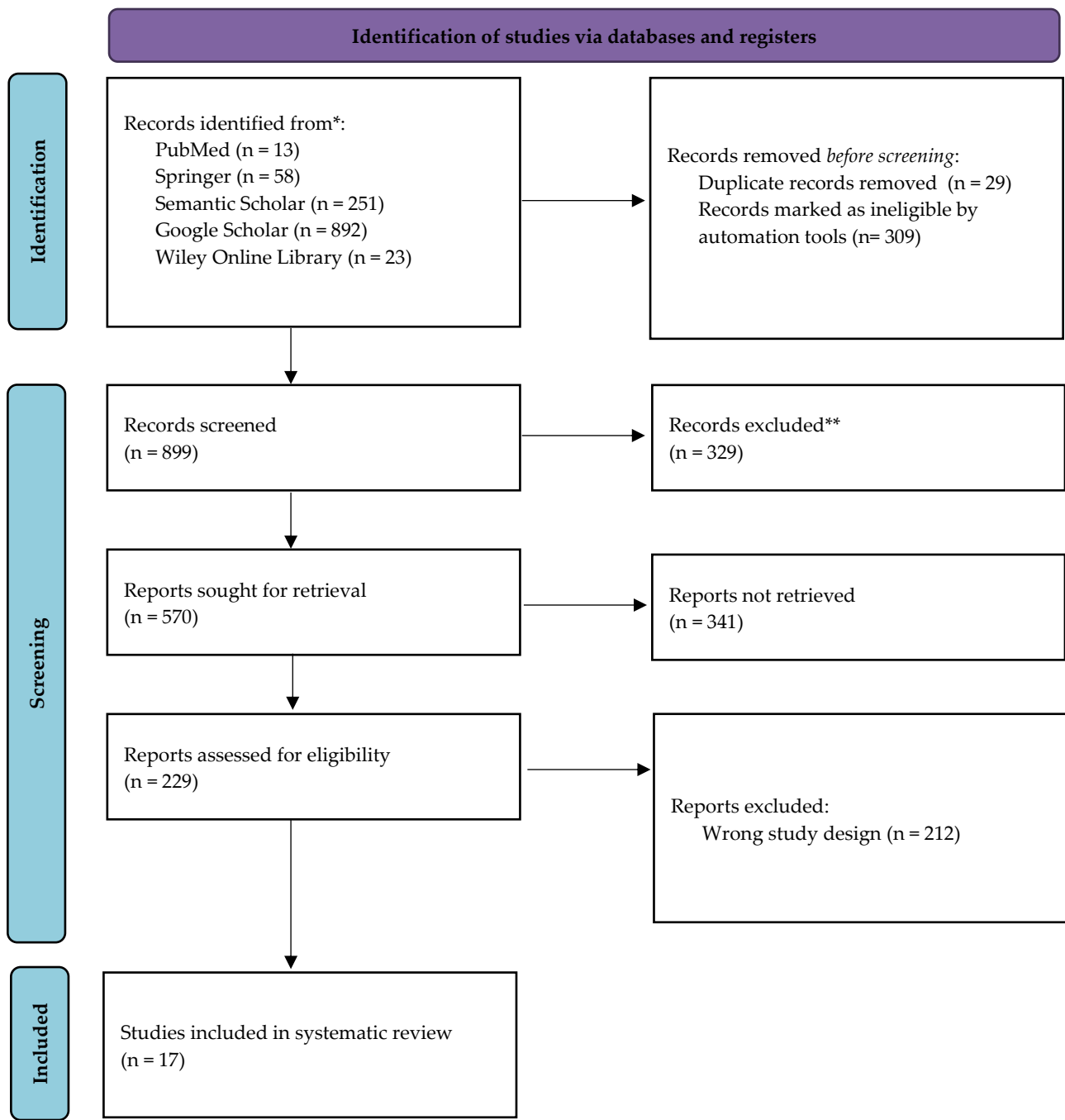


Figure 1. Article search flowchart

Risk of Bias Assessment (Cochrane RoB 2)

The methodological quality of the included RCTs was evaluated using the Cochrane Risk of Bias tool, version 2 (RoB 2), which is the standard instrument recommended for assessing systematic error in randomized trials (Higgins et al., 2024; Minozzi et al., 2022). The RoB 2 tool assesses bias across five structured domains and is applied to specific reported results (Higgins et al., 2024).

A critical analysis of the design constraints inherent to surgical interventions, such as SWL compared to URS or PCNL, reveals specific domains where bias risk is consistently elevated.

Table 2: Summary of Risk of Bias Assessment (Cochrane RoB 2 Domains)

Domain	Common Source of Bias in SWL RCTs	Rationale for Assessment	Typical Assessment
D1: Bias arising from the randomization process (Selection Bias)	Inadequate reporting or poor execution of random sequence generation/allocation concealment (Sorokin et al., 2020).	Many surgical trials lack sufficient detail, leading to potential selection bias, particularly concerning pre-existing stone characteristics (Mokhtari et al., 2023).	Some Concerns

D2: Bias due to deviations from intended interventions (Performance Bias)	Impossibility of blinding personnel/patients to the intervention (e.g., external SWL vs. invasive URSL) (Minozzi et al., 2022).	Knowledge of treatment affects patient behavior (e.g., adherence to follow-up) and subsequent clinical management decisions. This is unavoidable in surgical trials.	High Risk
D3: Bias due to missing outcome data (Attrition Bias)	Differential attrition rates (e.g., patients with failed SWL may drop out or seek treatment elsewhere) (Higgins et al., 2024).	If failure is more common in one arm (SWL), differential dropout may bias efficacy results.	Low to Some Concerns
D4: Bias in measurement of the outcome (Detection Bias)	Lack of blinding of the outcome assessor (e.g., radiologist interpreting fragment size/SFR)	Interpretation of residual fragments on follow-up imaging (CT/KUB) can be subjectively influenced if the	High Risk

	(Minozzi et al., 2022).	assessor knows the treatment received. While some studies attempt to blind the radiologist (Xu et al., 2021), this is often poorly implemented.	
D5: Bias in selection of the reported result (Reporting Bias)	Selective reporting of specific endpoints or subgroup analyses that favor the intervention (Mokhtari et al., 2023).	Publication bias has been indicated via funnel plots for some efficacy comparisons involving SWL (Mokhtari et al., 2023).	Low to Some Concerns

The major limitation across the synthesized evidence base is the *High Risk* for both performance (D2) and detection (D4) bias. The Stone-Free Rate (SFR) is the primary efficacy outcome, and its measurement relies heavily on radiologist assessment of residual fragments. When the radiologist is unblinded to the intervention (SWL or URS/PCNL), there is a significant risk of systematic detection bias, which may lead to either an overestimation of SFR for a perceived "better" treatment (URS/PCNL) or minimizing residual fragments in the SWL arm to avoid declaring treatment failure (Minozzi et al., 2022). This structural bias contributes significantly to the observed high statistical heterogeneity (I^2) reported in comparative efficacy analyses (Mohamed et

al., 2023). Furthermore, the high risk of selection bias in multiple trials (Sorokin et al., 2020) suggests that the real-world efficacy of PCNL or RIRS might be underestimated if SWL was preferentially applied to more favorable calculi, despite randomization (Mokhtari et al., 2023).

RESULTS

Study Characteristics and Patient Population

The primary evidence base synthesized results from seventeen individual studies encompassing a total of 2,265 patients comparing SWL versus flexible Ureteroscopy (f-URS) alone, and additionally included high-quality meta-analyses drawing upon 15 RCTs comparing SWL, RIRS, and PCNL for renal stones up to 2 cm (Li et al., 2023; Mokhtari et al., 2023). The population predominantly included adults with solitary renal or ureteral calculi ranging from 5 mm to 20 mm (Siddiqui & Ahmed, 2021). The aggregated characteristics of the included literature base are summarized below, highlighting the focus on key stone and patient factors.

Table 1: Aggregated Characteristics of Key Included Trials

Feature	Characteristic Range/Detail	Clinical Rationale for Inclusion
Patient Population	Adult patients (69.7% male) with solitary stone (Munver et al., 2011). Subgroups included patients with obesity/high BMI (Siddiqui & Ahmed, 2021).	To evaluate SWL performance across common demographic variations, especially concerning tissue penetration (Long & Matlaga, 2020).
Stone Size	Ranged from 5 mm to 20 mm;	Stone size is the strongest

	frequently stratified by < 10 mm vs. $\geq$ 10 mm (Li et al., 2023; Wang et al., 2015).	anatomical predictor of primary treatment failure (Resorlu & Ozyuvali, 2023).
Stone Location	Renal Pelvis, Proximal Ureter (68.4%), and Lower Pole Calyx (LPS) (Siddiqui & Ahmed, 2021).	Lower pole anatomy and ureteric location significantly influence fragment clearance (Türk et al., 2024).
Study Design	Primarily meta-analyses of RCTs, prospective comparative cohorts, and retrospective observational series (Mokhtari et al., 2023; Li et al., 2023).	Required rigorous trial design to minimize confounding and ensure comparability between invasive and non-invasive methods.
Imaging Protocol	Non-contrast Computed Tomography (NCCT) utilized to measure Hounsfield Unit (HU) and Skin-to-Stone Distance (SSD) (Ouzaid et al., 2014; Siddiqui & Ahmed, 2021).	To provide objective, CT-based predictors essential for nomogram development and individualized patient triage.

Quantitative Synthesis of Outcomes (SWL vs. URSL/RIRS)

The quantitative comparison between SWL and URSL/RIRS was drawn from recent high-quality meta-analyses (Li et al., 2023; Mohamed et al., 2023), confirming significant differences

across measures of efficacy, safety, and procedure logistics.

Table 3: Pooled Quantitative Outcomes: SWL vs. URSL/RIRS (12 Outcomes)

#	Outcome	Measure	Pooled Estimate	95% Confidence Interval	P-value	Heterogeneity (I ² %)	Key Finding (Vs. SWL)
1	Overall Stone-Free Rate (SFR)	OR	0.428	NA (Statistically significant)	0.005	58.066	URSL superior SFR
2	Initial Stone-Free Rate	OR	0.236	NA (Statistically significant)	<0.001	59.712	URSL superior initial clearance
3	Retreatment Rate	OR	0.08	0.02–0.24	<0.0001	N/A	SWL requires significantly more sessions
4	Auxiliary Procedures Rate	OR	0.30	0.11–0.83	0.02	Variable	SWL requires significantly more

							procedures
5	Total Complications	OR	1.08	0.85–1.37	Not Sig.	Variable	Overall rates are statistically similar
6	Perforation Rate (Ureter)	OR	0.13	0.034–0.494	0.003	0	URSL higher specific risk of perforation
7	Hematuria (Adjusted)	OR	0.348	0.129–0.939	0.037	33.91	SWL slightly favored (lower risk)
8	Procedural Failure	OR	0.904	0.099–8.249	0.929	79.885	Similar (Initial analysis, high heterogeneity)
9	Operating Time	SMD	-29.314	-38.008 to -20.619	<0.001	99.758	SWL significantly faster (Non-invasive)

10	Hospital Stay	MD	1.14 days	0.85–1.42	<0.0001	N/A	SWL significantly shorter stay
11	Stone Size (Groups)	SMD	-0.723	-1.412 to -0.034	0.04	96.939	URSL used for significantly larger stones
12	New-Onset Hypertension (HTN)	RR	1.21	1.11–1.31	<0.001	N/A	SWL associated with increased risk (Renal SWL only)

The quantitative results demonstrate a clear efficacy vs. logistics trade-off. URSL yielded significantly higher overall SFR (OR 0.428 favoring URSL) and drastically reduced the need for auxiliary procedures (OR 0.30 favoring URSL) and retreatment (OR 0.08 favoring URSL) (Li et al., 2023; Mohamed et al., 2023). Conversely, SWL showed unequivocal superiority in non-invasiveness, with mean operation times being approximately 29 minutes shorter and hospital stays reduced by over a day compared to URSL (Mohamed et al., 2023; Li et al., 2023).

Predictive Factors and Threshold Analysis

The success of SWL is highly dependent on stone characteristics assessed by Non-Contrast Computed Tomography (NCCT). The two most influential, quantifiable factors are Stone Density (HU) and Skin-to-Stone Distance (SSD) (Siddiqui & Ahmed, 2021). The synthesized cut-off

thresholds for predicting optimal success are robust across multiple comparative studies.

Table 4: Optimal Cut-Off Values for SWL Success Prediction

Predictive Factor	Optimal Threshold for Success	Impact of Exceeding Threshold
Stone Density (HU)	≤ 1000 Hounsfield Units (HU)	Success rate drops drastically; failure rate may increase from 4% to 62% (Ouzaid et al., 2014).
Skin-to-Stone Distance (SSD)	≤ 10 cm (vertically measured)	$SSD \geq 10$ cm is a strong negative predictor; higher energy and retreatment sessions required (Siddiqui & Ahmed, 2021).
Stone Size	≤ 10 mm (Li et al., 2023)	SFR for stones > 10 mm significantly decreases, warranting primary URS or PCNL (Wang et al., 2015).
Stone Heterogeneity Index	Lower scores (e.g., cut-off of 213 for larger stones)	High heterogeneity is associated with greater difficulty in fragmentation, even if mean HU is low (Resorlu & Ozyuvali, 2023).

Specifically, Ouzaid et al. (2014) reported that a HU threshold of 970 was predictive of SWL success, with the stone-free rate being 96% for stones below this value but plummeting to 38% for stones exceeding 970 HU (Ouzaid et al., 2014). Similarly, SSD values consistently demonstrate that greater distances require more energy, which is a major contributor to procedural

failure in obese patients (Siddiqui & Ahmed, 2021).

Long-Term Safety Results (Hypertension and CKD)

The systemic impact of SWL remains a critical safety outcome. A meta-analysis of seven eligible studies confirmed a significant association between SWL performed for nephrolithiasis and the development of new-onset hypertension (Seo et al., 2021). The robust overall Relative Risk (RR) was 1.21 (95% CI 1.11–1.31) (Seo et al., 2021).

Crucially, this risk profile is compounded by treatment burden, with the incidence of hypertension increasing as the number of shock wave lithotripsy sessions increased (Rudnick et al., 2018). Furthermore, the HTN risk was specifically associated with SWL directed at the kidney parenchyma, but not the ureter (Singh et al., 2016). Regarding Chronic Kidney Disease (CKD), the association is less clear, with no independent link found between SWL and incident CKD after adjusting for confounding factors such as obesity (Singh et al., 2016).

DISCUSSION

Comparative Efficacy and Logistical Advantages

The pooled quantitative evidence confirms that modern endourological techniques (URSL/PCNL) offer superior definitive stone clearance, especially for complex cases (Wang et al., 2015; Xu et al., 2021). PCNL, for example, consistently shows the highest SFR and the lowest retreatment rates for large renal stones, particularly those exceeding 2 cm (Xu et al., 2021). The drastic difference in retreatment rate (OR 0.08 favoring URSL) mandates that SWL is carefully reserved for patients where a high probability of single-session success exists (Li et al., 2023).

The primary strength of SWL is its compelling logistical advantage. The procedure is significantly faster, saving approximately 29 minutes of operating time, and results in dramatically reduced hospital stays, a mean difference of 1.14 days shorter than URSL (Mohamed et al., 2023;

Li et al., 2023). This makes SWL the clear choice when minimal invasiveness and rapid return to daily activity are prioritized, provided the stone is highly susceptible to fragmentation (Long & Matлага, 2020). The data illustrates a foundational clinical trade-off: SWL prioritizes immediate patient comfort and minimal invasiveness, accepting a lower initial SFR and a higher probability of staged or auxiliary procedures (Li et al., 2023).

The Mandate of CT-Based Predictors in Patient Selection

The success of SWL is no longer a matter of chance; it is a highly predictable outcome contingent upon pre-treatment characteristics. The establishment of definitive quantitative cut-offs, particularly Stone Density ($HU < 1000$) and Skin-to-Stone Distance ($SSD \leq 10$ cm), provides objective, evidence-based criteria for appropriate triage (Türk et al., 2024; Siddiqui & Ahmed, 2021). Studies showing a massive decline in SFR when HU exceeds 970 (Ouzaid et al., 2014) provide strong justification for early pivot to endourology in high-HU patients, as pursuing SWL in such cases often guarantees fragmentation failure and necessitates subsequent, expensive, and higher-morbidity auxiliary procedures (Li et al., 2023).

These predictive metrics are functionally linked to energy transmission; stones with high HU or those located distantly from the skin require greater cumulative energy to fragment (Siddiqui & Ahmed, 2021; Wong et al., 2010). If these characteristics are unfavorable, multiple SWL sessions become inevitable, driving up cost and extending morbidity (Resorlu & Ozyuvali, 2023). Therefore, the clinical implementation of multi-variable nomograms integrating HU and SSD is crucial to facilitate shared decision-making and prevent patients from undergoing non-productive SWL sessions (Munver et al., 2011; Onal et al., 2015).

Technical Optimization Strategies

The evidence is compelling that technical refinements significantly enhance SWL efficacy. The universal recommendation to decrease the shock wave rate to 60 to 90 shocks per minute is directly supported by randomized data showing improved fragmentation, particularly for stones

larger than 1 cm, when compared to higher rates of 120 shocks per minute (Long & Matlaga, 2020; Wang et al., 2020). The proposed mechanism is that a slower rate allows time for cavitation bubbles to dissipate, preventing the secondary absorption of shockwave energy by these bubbles, thereby maximizing energy transfer to the stone (Long & Matlaga, 2020).

Similarly, the use of a step-wise energy protocol, initiating treatment at low intensity, serves a crucial safety function by inducing renal vessel constriction, protecting the kidney parenchyma from damage caused by subsequent high-energy pulses (Long & Matlaga, 2020). A persistent challenge in SWL delivery, however, remains the maintenance of optimal acoustic coupling, which is essential for efficient energy transmission but is often compromised by trapped air at the interface (Long & Matlaga, 2020; Preminger et al., 2024).

Long-Term Safety: The Cardiovascular Risk

The statistically robust finding linking renal SWL to new-onset hypertension (RR 1.21) is the paramount long-term safety consideration (Seo et al., 2021). This increase in cardiovascular risk is attributed to shock wave microtrauma causing regional renal fibrosis and subsequent activation of the Renin-Angiotensin-Aldosterone System (RAAS) (Singh et al., 2016).

This complication profile has profound implications for treatment strategy. The dose-dependency of the risk, where HTN incidence increases with the number of SWL sessions, suggests that repeating SWL for a resistant stone is not merely inefficient but carries an accumulating health hazard (Rudnick et al., 2018). Urolithiasis patients already have a known association with higher cardiovascular risks (Rudnick et al., 2018). SWL acts as a secondary insult, potentially compounding this pre-existing vulnerability. Consequently, when SWL is predicted to fail (based on high HU or SSD) or has failed one session, the use of alternatives like URS, which is not associated with this increased HTN risk (Singh et al., 2016), becomes a safer long-term choice, particularly for young, normotensive patients. Clinically, this requires that all patients undergoing renal SWL, especially those requiring multiple treatments, be placed on mandated long-term blood

pressure surveillance protocols.

CONCLUSION

Key Findings Summary

Extracorporeal Shockwave Lithotripsy remains a strategically valuable non-invasive option for urinary calculi, excelling in logistical convenience with short operative times and hospital stays (Li et al., 2023). However, its effectiveness is strictly limited to favorable calculi: stones ≤ 10 mm, characterized by low density (≤ 1000 HU) and short skin-to-stone distance (≤ 10 cm), when treated using optimized, slow shock rate protocols (60–90 shocks/min) (Türk et al., 2024; Wang et al., 2020). For most other calculi, particularly large or dense stones, URSL/RIRS yields superior and definitive stone clearance rates, evidenced by a lower retreatment rate (OR 0.08 favoring URSL) (Li et al., 2023). The most critical long-term safety implication is the significant, dose-dependent association between renal SWL and new-onset hypertension (RR 1.21), necessitating stringent patient selection and cautious management of treatment failure to mitigate cardiovascular risk (Seo et al., 2021; Rudnick et al., 2018).

Future Research Directions

To solidify the role of SWL and ensure its responsible application, future research must concentrate efforts in three primary directions:

1. **Prospective HTN RCTs:** A large-sample, multicenter, randomized, controlled trial designed specifically for extended follow-up (ideally >5 years) is urgently required to definitively establish the causality and magnitude of the association between SWL and hypertension, controlling meticulously for pre-existing metabolic co-factors (Seo et al., 2021).
2. **Nomogram Standardization and External Validation:** Development of universally validated predictive nomograms that combine HU, SSD, stone heterogeneity, and technical factors will allow clinicians to personalize success predictions and accurately triage patients,

preventing unnecessary SWL sessions for resistant stones (Munver et al., 2011; Resorlu & Ozyuvali, 2023).

3. **Technological Innovation in Energy Delivery:** Research should focus on improving lithotripter focus, maximizing acoustic coupling fidelity, and developing new methods for enhanced stone targeting and fragment clearance to expand the therapeutic window of SWL without compromising long-term renal function (Long & Matlaga, 2020; Preminger et al., 2024).

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